NASA/CR–2002-211391
USAAMCOM AFDD/TR-02-A-003

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Piloted Simulator Investigation of Techniques to Achieve Attitude Command Response with Limited Authority Servos

David L. Key and Robert K. Heffley

Prepared for NASA Ames Research Center
under Contract NAS2-14360

January 2002

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NASA/TM–2002-211391
USAAMCOM AFDD/TR-02-A-003

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DEFINITIONS

AC Attitude Command

ACAH Attitude Command Attitude Hold

DVE Degraded Visual Environment, as defined in ADS-33D-PRF (Ref 1)

FPS Flight Path Stabilization

GVE Good Visual Environment

HH Height Hold control mode

HQR Handling Qualities Rating

K_p Gain in the lateral axis; roll rate

K_{phi} Gain in the lateral axis; attitude

K_q Pitch rate gain

Ksat Series servo percentage saturation

$K_{\theta P}$, Pitch attitude gain to the parallel servo

$K_{\theta S}$ Pitch attitude gain to the series servo

LASCAS Limited Authority Stability and Control Augmentation System

MTE Mission Task Element, as defined in ADS-33D-PRF (Ref 1)

NVG Night Vision Goggles

PIO Pilot Induced Oscillations

RC Rate Command

RCON6 Test configuration designation

RCON9 Test configuration designation

SAS Stability Augmentation System

SCAS Stability and Control Augmentation System

SP3A Test configuration designation

SP4A Test configuration designation

SP4B Test configuration designation

T_B Attitude feedback blend-out time

UCE Useable Cue Environment, as defined in ADS-33D-PRF (Ref 1)

x Earth axis forward displacement

y Earth axis lateral displacement

ω_{BW} Bandwidth frequency, as defined in ADS-33D-PRF (Ref 1)

τ_P Phase delay, as defined in ADS-33D-PRF (Ref 1)

SUMMARY

The purpose of the study was to develop generic design principles for obtaining attitude command response in moderate to aggressive maneuvers without increasing SCAS series servo authority from the existing ± 10%. In particular, to develop a scheme that would work on the UH-60 helicopter so that it can be considered for incorporation in future upgrades. The basic math model was a UH-60A version of GENHEL. The simulation facility was the NASA Ames VMS. Evaluation tasks were Hover, Acceleration-Deceleration, and Sidestep, as defined in ADS-33D-PRF for Degraded Visual Environment (DVE). The DVE was adjusted to provide a Usable Cue Environment UCE=2. The basic concept investigated was the extent to which the limited attitude command authority achievable by the series servo could be supplemented by a 10 %/sec trim servo. The architecture used provided angular rate feedback to only the series servo, shared the attitude feedback between the series and trim servos, and when the series servo approached saturation the attitude feedback was slowly phased out. Results show that modest use of the trim servo does improve pilot ratings, especially in and around hover. This improvement can be achieved with little degradation in response predictability during moderately aggressive maneuvers. This report describes the simulation set-up, discusses the results and provides some basic design principles for implementing such response types on a specific helicopter.

INTRODUCTION

Background

The current generation of US Army helicopters have flight control augmentation systems with actuator authority limited to nominally ± 10%. This limits response type to Rate Command (RC).

With RC, pilot workload increases and achievable task precision deteriorates in a degraded visual environment (DVE). Such conditions are typically encountered when vision aids are employed in non-ideal conditions (e.g., using night vision goggles (NVGs) on a moonless night). The effect of reduced visual cueing is twofold: 1) the pilot has problems seeing obstacles; 2) the ability to perceive fine-grained texture is degraded. Consequences of the former effect are obvious, and additional vigilance is required to avoid collisions with objects or the ground. Consequences of the second effect are not obvious or intuitive. The visual scene appears to be adequate for low speed and hover operations, but it is missing subtle cues that are necessary for precise attitude and position control. Flight path control precision is reduced even as the amount of required pilot attention increases. In addition, undetected drift can arise, resulting in collisions with the ground or nearby objects. In controlled test conditions, flight in the DVE is manifested as an apparent degradation in handling qualities. Precise control requires intensive workload, leaving little or no excess workload capacity to maintain situation awareness or accomplish the mission tasks.

Results from ground-based and in-flight simulations have shown that attitude stabilization (Attitude Command Attitude Hold ACAH) is an effective means to compensate for the handling qualities problems that occur when flying in a DVE. The US Army Aeronautical Design Standard for Handling Qualities of Military Aircraft, ADS-33D-PRF (Ref. 1) therefore requires that ACAH be available in DVE calibrated as a Usable Cue Environment UCE=2.

In a helicopter with a full authority fly-by-wire flight control system, such as the RAH-66 Comanche, ACAH is achievable and is provided in the design. However, the rest of the current US Army fleet use hydro-mechanical systems,not fly-by-wire. They have Stability and Control System Augmentation (SCAS) actuators to provide stabilization, but for safety in the event of failures, authority is limited to nominally ± 10%. Such limited authority SCAS (LASCAS) have hither-to provided only rate damping, or perhaps rate command attitude hold. Achieving pure ACAH requires the SCAS series actuator to have almost as much authority as the pilot. However, it may be possible to provide the stabilization benefits of ACAH for gentle to moderate maneuvers but remove the attitude stability during aggressive maneuvers. The advantage of this would be the ability to retrofit existing helicopters with new control laws, while requiring virtually no changes to the hydro-mechanical portions of the flight control system hardware.

Several experiments have been performed to investigate techniques for achieving the benefits of ACAH without increasing the actuator authority (Refs 2 - 6). The results suggest that much improved handling qualities can be achieved with up to moderate levels of maneuvering aggressiveness. However, the level of aggressiveness at which the servo saturates, and the effective handling qualities when in saturation, will depend on the basic helicopter's dynamic characteristics. A possible candidate for applying ACAH to upgrade an existing US Army helicopter is the UH-60M upgrade. In the Ref. 3 and 5 trials, it was not possible to simulate a basic helicopter with long term damping ratio as unstable as the UH-60, so the question remained as to what effect this may have on the results. It was therefore decided to select the most promising technique from Ref. 5 and determine how good it could be made for the UH-60. The trials described in this report were performed in August and September 1998 using the NASA Ames Research Center Vertical Motion Simulator (VMS).

Objectives

The primary objectives of this simulation were:

1. To build on the past work to develop generic principles for LASCAS design for incorporation into future design guides.
2. To refine the concepts to ensure that handling qualities remain safe even in very aggressive maneuvers.
3. To develop a scheme that should work on the UH-60 helicopter so that it can be considered for incorporation in future upgrades.

Overview of Limited-Authority ACAH Flight Control Systems

Limited-authority flight control systems are commonly used on current military rotorcraft. A functional schematic of such a system is shown in Fig 1. In this system the series servo provides inputs to the swashplate without feedback to the pilot's control stick (i.e., the servo is in series with the pilot). The trim servo is typically activated by the pilot's trim switch, but can also be driven by feedback from aircraft states as is the case in typical autopilot functions. Movement of the trim servo causes not only a change in the swashplate but is also reflected directly at the stick (i.e., the trim servo is in parallel with the pilot).

The series servo is typically fast (order of 100%/sec), but authority is limited to approximately ±10% of equivalent pilot stick travel to protect against hardover failures. That is, if the series servo fails hardover, the pilot has 90% of the control to counteract the 10% hardover. Any modifications to this authority could involve significant changes to the hardware, and would require airworthiness re-qualification, not only for the new hardware, but also to assure that the pilot can recover safety in the case of hardover failures. This would be very expensive. It has therefore been taken as a given that a practical addition of ACAH stabilization requires that it be accomplished with the existing series servos.

The parallel or trim servos typically have full authority, but are rate-limited to approximately 10% of full travel per second. This is done to protect against excessive transients in the event of a trim runaway. If the trim servo is used to augment the attitude feedback the augmentation feedback will be felt by the pilot at the control stick and will modify the stick free dynamics (response to pilot's control force inputs) to be different from the stick fixed dynamics (response to the pilot's control displacement inputs).

The primary handling qualities issues then that must be considered in devising control system architectures that approximate a full-authority ACAH are:

1. Series servo position limiting,
2. Parallel servo rate limiting,
3. Control stick motion and modified stick free dynamics

Position limiting on a limited-authority system will cause the response to transition from ACAH to the unaugmented rate-like dynamics. This could be favorable or unfavorable.

If the unaugmented aircraft is well damped, then the transition to the unaugmented dynamics following the demand for a large attitude change can appear to the pilot as a smart switch to a Rate Response-

Type. This will increase maneuvering agility and could overcome the primary drawback of ACAH and make it desirable even for day GVE operation.

On the other hand, if the dynamics of the augmented aircraft are significantly different from those of the unaugmented aircraft, the pilot may find the response unpredictable and have difficulty adapting. This could be particularly bad if the unaugmented aircraft is unstable or only lightly damped.

Some insights into the effect of stick motion in response to parallel servo force cues were obtained from the Ref. 5 flight test and the Ref. 4 simulation. Stick movement for autopilot functions is widely accepted, but it was initially thought that stick motions would be objectionable during precision maneuvering flight. This hypothesis was not confirmed. It turned out that some pilots did object to the stick motion, especially in the aggressive maneuvers, while others did not find it objectionable. The analysis of the data in Ref. 5 suggested that the unfavorable effects of stick motion may be primarily due to poor stick-free dynamics which resulted when the parallel servo reached its rate limits.

Augmentation Configurations

Based on the results of Ref. 5 it was decided to restrict this simulation investigation to the split path (SP) control system architecture. This architecture simply splits the attitude feedback between the series and parallel servos. Attitude feedback goes to both the series and parallel servos, but is blended out from the series servo before the servo reaches its authority limits. Angular rate is fed only to the series servo. The pitch-rate and roll-rate signals are fed back to only the series servos, because the higher-frequency nature of changes in angular rate would be certain to reach the parallel actuator rate limit. The block diagram in Figure 2 describes the implementation of the limited-authority system for the longitudinal axis. The control system architecture for the lateral axis is similar to the longitudinal axis.

The tradeoff between stick motion and series servo saturation is easily studied with this mechanization. If $K_{\theta S} >> K_{\theta P}$, the stick motion due to attitude stabilization feedback will be small. Most of the signal will pass through the series servo and there will be a tendency for saturation if pitch attitude is increased to moderate values. If $K_{\theta S} << K_{\theta P}$ the stick motion will be large but the series servo will have less tendency to saturate. Configurations ranged from SP1, where $K_{\theta S} >> K_{\theta P}$ to SP4, where $K_{\theta S} << K_{\theta P}$.

During the in-flight simulator testing in Ref. 5 it was found desirable to blend the attitude feedback signal out when the series servo was saturated. This caused the servo to become unsaturated so that the beneficial effects of the rate damping feedback could be retained. This attitude "blend-out" function is represented by the blend multiplier in the Figure 2 block diagram. The blend was achieved with a limited integrator with input $1/T_B$ to produce a linear blend-in and blend-out of pitch attitude over T_B seconds. The Ref. 5 flight testing showed that short blend times (1 to 3 seconds) resulted in undesirably abrupt attitude commands. A blend time of 5 seconds produced a smooth blend.

It was also found desirable to initiate the blending before actual saturation occurred. This is achieved with the Ksat term in Figure 2. In the flight tests, Ksat was nominally set to 0.80 to cause the blending to start when the input to the series servo reached 80% of saturation. Unfortunately, due to an oversight, this parameter Ksat was set at 1.0 in this study.

It is difficult to visualize the effect of series actuator limits (saturation) in terms of control system travel. A more useful metric is to define the attitude command authority as the rotorcraft attitude where saturation occurs if the angular rates are zero. Thus $\theta_{sat} = \delta_{sat} / K_{\theta s}$

SIMULATION SET-UP

This experiment was performed shortly after the PAFCA trials, Ref. 7, which had similar objectives, but a different control law design philosophy. The PAFCA ACAH control laws were developed using only the series servo. One approach optimized the gains to match ADS-33D-PRF handling qualities criteria, and the other approach minimized the mismatch between the open and closed loop frequency response, and allowed the ADS-33D-PRF criteria to be compromised. Because of the similarity with PAFCA, much of the simulator set-up was carried over to these trials without change.

Facility

The cockpit was configured for one pilot with conventional UH-60 cyclic and collective controls and representative analog flight instruments. The out-the-window scene was presented by a 4 window Evans and Sutherland ESIG 4530 computer generated imagery display. This was set-up to provide adequate cues when viewed directly with full color and contrast, and represented a "day" Good Visual Environment (GVE). This "day" environment was used to train the pilots so that they were familiar with the configuration response and the task before going to the degraded visual environment (DVE) night scene. To simulate the DVE, the image generator was set to a night scene and viewed through ANVIS-6 night vision goggles. This DVE was assessed in PAFCA (Ref. 7) to give the UCE=1 for the acceleration-deceleration task and UCE=2 for the sidestep and hover tasks.

The NASA Ames Vertical Motion Simulator (VMS), was set-up with motion gains optimized for each task. To take advantage of the large sway travel, the cockpit was rotated 90 deg from the standard heading when performing the acceleration deceleration maneuver.

Helicopter Math Model

The math model used was the Sikorsky GENHEL UH-60A (Ref. 8) as programmed for real time operation by NASA Ames Research Center. This model uses a blade element rotor model with flap and lag degrees of freedom, and static look-up tables for blade and fuselage aerodynamics and rotor downwash. The rotor rpm degree of freedom and T700 engine and governor were included.

ACAH Control Law Design

It was originally planned to use a fairly simplified math model, but results from the PAFCA program immediately preceding this VMS entry showed that significant actuator authority was being consumed by the attitude hold, just to maintain trim. The large trim change could not be reproduced by the simplified math model, so it was decided to revert to GENHEL for the trials. This late change made it impractical to develop linearized versions to use for control law synthesis, so augmentation gain settings were restricted to simple on-axis attitude and rate feedbacks. Thus pitch attitude and rate were fed to the longitudinal control axis and roll attitude and rate were fed to the lateral axis through the parallel (trim) and SAS servos as shown in Figure 2. These inputs passed through the mechanical mixing box so were equivalent to inches of pilot stick deflection. The collective axis was modified to provide Height Hold. The yaw axis was not modified from that of the basic aircraft.

The ratio of attitude feedback to the parallel actuator compared to the series actuator was varied from 1:3 to infinity (i.e. all attitude feedback to the parallel servo). This gave a range of attitude command authority, at zero rate, from 5.2 deg. to infinity. Table 1 shows the matrix of gains used. Using just attitude and rate feedback, the response was tailored to give a nominal bandwidth of 2.0 r/s in pitch and 4.0 r/s in roll. The basic UH-60 with Height Hold added was used as a reference or baseline.

Table 2 shows the bandwidth frequencies and phase delays actually achieved for all of the tested configurations, including the standard UH-60A model with SAS and FPS on, and the frequency match design configuration from PAFCA (Ref. 7). Attitude feedback to the parallel servo causes the response to control force to be different from the response to control displacement. Based on the phase delay definition of bandwidth, the bandwidth frequencies in response to control displacement are slightly higher than in response to control force. The phase delays in response to displacement are in the range of 0.1, which is satisfactory. However, the phase delays in response to force, for pitch, range from 0.23 to 0.31 which sets them in the Level 3 area. Roll is slightly better, with phase delays ranging up to 0.2, marginally Level 2. The gain margin bandwidths in response to displacement are just greater than 1.0 for pitch, and range up to 2.0 for roll. In response to force, the gain margin bandwidths are largely indeterminate. Pitch and roll Bode plots for configuration SP4B are provided in Figure 3.

Figures 4-9 show step responses to control force and displacement inputs for SP1A, SP3A, and SP4B. As can be seen, not all of the configurations demonstrate an ideal attitude command step response consisting of a smooth capture of a new attitude which then remains essentially constant between 6 and 12 seconds. However, most meet the alternative part of the ADS-33D-PRF (see Appendix A) definition of attitude command in that the translational acceleration is constant or asymptotically decreasing towards a constant. The quality of Attitude Command implied by the step responses are summarized for configurations SP1A and SP4B in Table 3. Based on such considerations the following HQ may be expected.

Predicted HQ based on ADS-33 criteria

In ADS-33 bandwidth is determined by frequencies related to a gain margin or a phase margin. For rate response types, bandwidth is defined as the lesser of these two frequencies. For ACAH response types bandwidth is defined as the frequency determined by phase margin, but cautions that if the gain determined frequency is less than the phase determined frequency, or if the gain related frequency is indeterminate, then the configuration may be PIO prone in precision or aggressive tasks. Table 2 shows that for all of the SP configurations, the bandwidth frequencies determined from gain margins are less than from phase margins or are indeterminate, thus are potential candidates for PIO.

SP1A

Based on the phase definition of bandwidth this configuration had good Level 1 bandwidth in roll. In pitch, the bandwidth was Level 1 in response to control displacement, but Level 2 in response to force. The AC character was quite good, but limited to an authority of only 5.2 deg in pitch (6.7 roll). Most of the attitude feedback was to the series servo, with only modest feedback to the parallel servo. These characteristics would suggest that overall responses in both pitch and roll should be good, but the AC benefits would be available only in very gentle maneuvers. Stick motions in response to the parallel servo feedback should not be intrusive. Cross coupling was small, so should not be significant even in the aggressive parts of the maneuvers.

SP4B

For this configuration all of the attitude feedback was made to the parallel servo so attitude command authority for both pitch and roll was unlimited. The phase margin bandwidth remained Level 1 in roll, but for pitch deteriorated to solid Level 3 in response to force and Level 2 in response to displacement. However, note that in GVE (UCE=1) the pitch bandwidth would be Level 1, even with the very large τ_P, so the ratings for the acceleration and deceleration task should not be downgraded due to this factor. The pitch AC character in response to force or position remained similar to SP1A, that is, marginal. The roll AC character in response to force remained satisfactory, but deteriorated to unsatisfactory in response to displacement. These characteristics would suggest that pitch response would be noticeably sluggish, and AC marginal. The roll response would be sufficiently crisp, but may not provide the expected benefits of AC. Significant stick motions in response to the parallel servo feedback should be noticeable in both pitch and roll, and parallel servo rate limiting would be expected in moderate to aggressive maneuvers. SP4B tends to exhibit significant roll-due-to-pitch and pitch-due-to-roll cross couplings. The ADS-33D-PRF requirements 3.3.9.2 are strictly for aggressive maneuvering, so the HQ may not actually be Level 2 but would probably not be good.

Evaluation Methodology

Seven highly experienced rotorcraft test pilots participated in the trials. They represented US Army Aeroflightdynamics Directorate, NASA Ames Research Center, Navy Test Pilot School, and Sikorsky Aircraft. The evaluation tasks were selected from the version of ADS-33 that was current at the time, Ref. 1. These were the Degraded Visual Environment (DVE) Mission Task Elements of Hover, Acceleration and deceleration, and Sidestep. Descriptions of these tasks are reproduced in Appendix B. Time histories of each run were recorded. The pilots were allowed to fly each configuration in a task as many times as they needed to feel comfortable before making a rating; typically this was three times, occasionally four. To guide their evaluation the pilots were requested to answer the questions in the pilot questionnaire, Appendix C, finishing with a Handling Qualities Rating (HQR) using the Cooper-Harper HQR Scale, Ref. 9.

RESULTS

A total of 1632 individual runs were performed. The HQR assigned to all of the rated runs are given in Table 4 for the night (DVE) runs and Table 5 for the day (GVE) runs.

A composite plot of HQR maximum, minimum and average, with Height Hold on is shown on Figure 10

The effect of deleting Height Hold is shown on Figure 11.

The effect on HQR of changing to Day (UCE=1) visual cues is shown on Figure 12.

The effect of changing control force breakout and gradient is shown on Figure 13.

Time histories for a typical acceleration-deceleration maneuver for each of the configurations SP1A, SP3A, SP4B, and UH-60 are shown on Figures 14-17.

Time histories for a typical hover maneuver for each of the configurations SP1A, SP3A, SP4B, and UH-60 are shown on Figures 18-21.

Time histories for a typical sidestep maneuver for each of the configurations SP1A, SP3A, SP4B, and UH-60 are shown on Figures 22-25.

Abstracts of transcribed pilot comments for each of the configurations SP1A, SP3A, SP4A, SP4B, and UH-60 are provided in Appendix D

Abstracts of transcribed pilot comments for configurations SP3A and UH-60 with Height Hold on and off are provided in Appendix E

Abstracts of transcribed pilot comments illustrating the effect of stick force gradient and breakout on configuration SP4B are provided in Appendix F.

The primary benefit of ACAH is in degraded visual environments calibrated as UCE=2 or greater. In a UCE=1 ACAH provides little benefit and can in fact be detrimental if it inhibits maneuverability. As mentioned earlier it was found that UCE=2 for the Hover and Sidestep tasks, but UCE=1 for the Acceleration and deceleration. With this in mind, it is convenient to review the results of the various configurations grouped by task.

Acceleration and deceleration task

As expected, all of the SP configurations, and even the baseline UH-60 (HH on), were rated Level 1 average HQR in the acceleration and deceleration task (Figure 10)

In typical runs, all four configurations (SP1A, SP3A, SP4B, and the UH-60) show a clean acceleration and deceleration to capture hover (Figures 14-17). Pitch and roll series servos show signs of saturation at the initial acceleration. Almost continual oscillations of about ± 3 degrees of bank are apparent through the translation period. These oscillations do not show in the pitch axis, unlike in the sidestep task where SP1A and SP3A show significant oscillations in both pitch and roll (Figures 22-23).

SP3A exhibits less series servo saturation than SP1A at the initial acceleration.

SP4B not only exhibits more series servo saturation than SP1A at acceleration initiation, but also encounters saturation at the end of the deceleration. It also shows parallel servo rate limiting at both ends of the run.

UH-60 is similar to SP1A but shows additional saturation of the series servos at the end of the deceleration.

From Figure 10 it can be seen that SP4A appears to have the best pilot ratings, but this configuration was only evaluated once by each of two pilots. Both evaluations were performed using relaxed lateral standards (desired were relaxed to adequate). This was to determine if the ratings were overly influenced by the difficulty of maintaining the tight lateral track when little could be seen over the nose during the deceleration portion. This relaxation did not seem to influence the HQR, but it did allow the pilot to be very perceptive about the force feedback from the parallel servo (see Appendix D, SP4A, pilot A run 965). Clearly, the enhanced stabilization provided by the high attitude command authority more than outweighed the disadvantages of the uncommanded stick movements. This opinion was implicitly reflected in the other pilot's comments (Appendix D, pilot T, run 962) who realized that the controls were quite active though he had not done much of the work. The modest precision requirements at the end of the task, and the fact that UCE=1 made the low bandwidth not an issue.

Hover task

Hover is probably the most difficult task to perform in the DVE (Appendix D, UH-60, pilot Gr, run 1404). The criticality of the task is mostly in quickly achieving the precise hover and then maintaining it for 30 seconds.

Time histories of typical hover runs are shown in Figures 18-21.

SP1A shows a very aggressive hover capture from a translational velocity of greater than 10 ft/sec. There is little overshoot in x and y at the hover position. Noticeable saturation of the series servo occurs at the hover capture, but there are no signs of parallel servo limiting. There are distinct signs of PIO (large amplitude stick force and position oscillations) during the hover capture.

SP3A achieves a hover capture that is even more aggressive than shown by SP1A. This aggressive capture results in noticeable saturation of the series servos and rate limiting of the parallel servos. As with SP1A there are distinct signs of PIO during the hover capture.

SP4B achieved a much slower, less aggressive hover capture than SP1A and SP3A, though still within the desired tolerances. This more relaxed capture did not cause any signs of series or parallel servo saturation, and control oscillations were less apparent.

UH-60 achieved a capture comparable to SP4B, but the subsequent hover was noticeably less precise with the longitudinal position wandering off.

In this task, stabilization ability is probably more important than large attitude authority. This is reflected in the HQR. SP1A and SP3A achieve the most improvement from the UH-60 baseline with an average HQR of about 3.7. The pilot comments seem to confirm this. SP1A had no particular deficiencies (Appendix D: SP1A, pilots A, G, H, and W).

On SP3A, several of the pilots commented that the pitch axis is somewhat marginal though stable once established in the hover. This is probably due to the marginal bandwidth that resulted from the excessive attitude feedback to the parallel servo.

SP4A and SP4B received noticeably worse ratings than SP1A and SP3A, probably due to the reduced bandwidth and degraded AC as predicted above. Several of the pilots noticed the significant stick motions caused by the large feedback to the parallel servo, but only pilot H downrated the configuration explicitly because of stick motions (Appendix D, SP4B, pilot H, run 1271). The more modest stick motions of other configurations were noticed, but did not cause particular concerns.

Sidestep task

The sidestep task demands aggressive bank angle changes. It is probably the critical maneuver for limiting saturation and nonlinearities in roll, and for cross coupling at the roll-in and roll-out. There is still a need for good stabilization at the end, though not for as long as the hover, nor with such precision.

Time histories of typical sidestep runs are shown in Figures 22-25.

SP1A shows good acceleration to about 30 ft/sec followed by a clean deceleration to hover. Series servo saturation is noticeable in both pitch and roll. This saturation starts at roll-in to the sidestep, and continues throughout the translation as the pitch and roll attitudes oscillate.

SP3A shows series servo saturation and pitch and roll oscillations that are similar to those exhibited by SP1A. In addition, it has noticeable rate limiting in the parallel servos. The sidestep roll-in and roll-out are cleanly done, but there is a large overshoot in longitudinal position at the end.

SP4B shows no series or parallel servo limiting during any part of the run. Pitch and roll oscillations are greatly reduced from those of SP1A and SP3A. Significant oscillations occur in the pitch and roll stick forces and displacements during the hover capture, perhaps indicating a tendency to PIO. Final capture of the hover seems well done.

UH-60 shows no sign of servo limiting. Oscillations are apparent in the pitch and roll rates and the longitudinal position capture overshoots somewhat.

SP4A and SP4B, the two configurations with large attitude command authority have the best ratings, but a wide divergence of opinion (Appendix D). Pilot H downrated SP4B because of confusing characteristics (HQR 6). Pilot A noticed the stick feedback, let it do the stabilization, and achieved desired performance (HQR 3). Only pilot A rated the sidestep in SP4A. He noticed the sluggish behavior, but as with SP4B he took full advantage of the high gain stick feedback and achieved Level 1, (HQR 2 and 3). Neither SP1A nor SP3A was downrated for any specific deficiencies, the problem was that most of the pilots just could not achieve the desired performance without excessive compensation.

PIO tendencies

As discussed in the section on Predicted HQ based on ADS-33, each of the configurations had lower frequency for gain margin bandwidth than phase margin bandwidth. Such configurations may be PIO prone. This indeed was the case. The pilot commentary (Appendix D) contains at least one reference to PIO tendencies on each of the configurations SP1A, SP3A, SP4A, and SP4B, for at least one of the tasks. However, as expected with a ACAH response type, if the pilot backed out of the loop and let the stabilization system do its job, the PIO generally abated and control was maintained. This technique was commented upon several times. Some examples:

SP1A: Pilot A, hover and sidestep. Pilot T, hover.

SP3A: Pilot A, acceleration-deceleration and hover. Pilot H, hover and sidestep. Pilot T, hover. Pilot W hover.

SP4A: Pilot A, hover and sidestep.

SP4B: Pilot A, sidestep. Pilot H, sidestep.

Effect of Height Hold

Overall the effect of HH is some improvement in the HQR, though the benefit varies with configuration and task (Figure 11). Most benefit from HH (or most degradation when turned off) occurred with the configuration SP3A, where the average HQR improved more than 1.5 points for each of the three tasks. The HQR plots suggest that the benefit of ACAH as represented by SP3A would be completely lost without HH. With the UH-60, the only change was in the hover task, where HH improved HQR by 1.5 points. RCON6 also demonstrated no improvement with HH.

Summaries of pilot commentary for configurations SP3A and UH-60 with Height Hold on and off are given in Appendix E.

Acceleration and deceleration

While performing the acceleration deceleration task pilot A made a big point of the difficulty of height control with SP3A HH off. These runs were made early in his VMS experience and he was still learning to compensate for the minimal acceleration cues.

Pilot T also had more difficulty with HH off, in SP3A.

Hover

As with the acceleration and deceleration task, in hover there was very little benefit noticed from HH on the UH-60. However, with SP3A there was a noticeable improvement obtained from HH.

Sidestep

While performing the sidestep task with the UH-60 configuration, both pilots gave a worse rating HH on than with HH off. Pilot W did notice some improvement HH on with the SP3A. In both the UH-60 and SP3A, the sidestep task seemed to be dominated by the difficulty of maintaining longitudinal position, and HH was essentially in the noise.

Effect of Stick force gradient and breakout

Attitude feedback to the parallel servo results in stick motions that the pilot can follow or resist. The intensity of these cues is dependent on the breakout and gradient in the feel system, so these characteristics could be a quite important influence on the acceptability. One pilot made several comments about the stick forces especially with configuration SP4B (see Appendix D pilot Gr, run 1458). To investigate this parameter several variations were made to the breakout and gradients. Figure 13 shows the HQR achieved. Appendix F provides some of the associated pilot comments.

The HQR on Figure 13 suggest that increasing the pitch control force gradient from 0.7 lb/in to 1.5 lb/in had a noticeably detrimental effect on the acceleration and deceleration task. The hover HQR were improved by almost one pilot rating by reducing the roll force gradient from 1.0 lb/in to 0.7 lb/in. A similar change made essentially no difference to the HQR for the sidestep task.

Pilot commentary in Appendix F do not provide any indication that the pilots were explicitly aware of these very slight changes to the forces, but certainly the overall HQ was affected. This suggests that part of a development program to achieve LASCAS should include some optimization of the stick forces.

CONCLUSIONS

It is possible to achieve Level 1 ACAH HQ with series actuator authority limited to 10% and trim servo rate limited at 10 %/sec.

The split path architecture tested can provide Level 1 in gentle maneuvers and provide better HQ than RC or RCAH. It provides desirable response in moderately aggressive maneuvers, certainly in most maneuvers to be expected in DVE. When either the series or parallel servo saturate, the nonlinearities are acceptable; the responses change but are still reasonably predictable and should not lead to PIO.

Increasing the authority of attitude command by using feedback to the parallel servo does improve the handling qualities up to a point. It does not seem that excessive stick motions are of concern to most pilots. Rather, the primary phenomena limiting high attitude authority is degraded bandwidth resulting from the poor dynamics of the parallel servo. The suggested criteria is to limit the attitude authority to feedback levels which maintain Level 1 phase margin based bandwidth in response to both force and displacement control inputs. In addition, the gain margin based bandwidth should be kept high, or as close as possible to the phase margin defied bandwidth.

Other recommended design principles, not varied here but carried over from previous trials, include blending out the attitude feedback at 80 to 100% of the saturation authority, and a blend out rate of 5.0 seconds.

Any development program to achieve LASCAS in a particular helicopter should include some optimization of the stick breakout and gradient forces.

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TABLES

Table 1: Matrix of gains for split path configurations.

Parameter	Configuration			
	SP1A	**SP3A**	**SP4A**	**SP4B**
	Most attitude feedback to series servo	Most attitude feedback to parallel servo	All attitude feedback to parallel servo, roll only	All attitude feedback to parallel servo
Longitudinal AXIS				
Parallel: series ratio	1:3	10:1	10.1	infinity
Attitude cmnd authority, deg	5.2	41.7	41.7	infinity
Parallel K_{thet} in/deg	0.032	0.116	0.116	0.128
Series K_{thet} in/deg	0.096	0.012	0.012	0
Series K_q in/deg/sec	0.074	0.074	0.074	0.074
Lateral AXIS				
Parallel: series ratio	1:3	3:1	infinity	infinity
Attitude cmnd authority, deg	6.7	20	infinity	infinity
Parallel K_{phi} in/deg	0.025	0.075	0.1	0.1
Series K_{phi} in/deg	0.075	0.025	0	0
Series K_p in/deg/sec	0.25	0.25	0.25	0.25

Table 2: Bandwidth parameters achieved for tested configurations

	UH-60	**SP1A**	**SP3A**	**SP4A**	**SP4B**	**RCON6**
Pitch						
ω_{BW} Displacement	2.8/ 0.9	2.1/ 1.3	1.9/ 1.1	1.9/ 1.2	1.5/ 1.1	1.7/ 1.5
τ_P Displacement	0.12	0.1	0.1	0.1	0.09	0.1
ω_{BW} Force	2.1/ I	1.9/ I	1.7/ I	1.7/ I	1.6/ I	1.2/ 1.5
τ_P Force	0.29	0.23	0.23	0.25	0.31	
ω_{BW} Force/Displ	15.8	15	13	15	14.3	10.5
Roll						
ω_{BW} Displacement	4.9/ 1.3	4.5/ 1.1	4.1/ 1.8	3.9/ 2.1	3.7/ 1.7	3.7/ 2.3
τ_P Displacement	0.12	0.09	0.11	0.09	0.11	0.1
ω_{BW} Force	3.3/ I	3.0/ I	2.9/ I	2.8/ I	2.8/ I	2.7/ I
τ_P Force	0.16	0.21	0.12	0.19	0.18	
ω_{BW} Force/Displ	16.6	20	17.8	15.1	16.4	13.1

Note: ω_{BW} = Bandwidth frequency (Phase limited/ Gain limited)
I = Indeterminate

Table 3: Comparison of force and displacement responses for SP1A and SP4B

Response parameter	SP1A		SP4B	
	Character of response	Implied Level	Character of response	Implied Level
Pitch response to force				
Bandwidth ω_{BW} / τ_P	1.9 / 0.23	L 2	1.6 / 0.31	L 3
Character of Attitude Command (1.5 lb step)	Peaks at 3 sec, returns to within 10% by 7 sec. But translational acceleration tends to zero at 6 to 12 sec	Marginal L 1	Peaks at approximately 3 sec, within 10% by 10 sec. Translational acceleration decreasing slowly	L2
Cross coupling (Roll/pitch at 4.0 sec)	0.15	L 1	0.4	L 2
Gearing (attitude deg/lb stick at 4.0 sec)	9		3	
Pitch response to displacement				
Bandwidth ω_{BW} / τ_P	2.1 / 0.1	L 1	1.5 / 0.09	L 2
Character of Attitude Command (0.35 in step)	Good attitude change, and translational acceleration tending to zero for 0.35 in input. Rate-like attitude response for 0.5 in input	Marginal L 1	Does not hold attitude, slow increase to a max at about 7 sec. But translational acceleration does tend to zero at about 10 sec.	Marginal L 1
Cross coupling (Roll/pitch at 4.0 sec)	0.3	L 2	0.5	L 2
Gearing (attitude deg/inch stick at 4.0 sec)	8 to 10		27	
Roll response to force				
Bandwidth ω_{BW} / τ_P	3.0 / 0.21	L 1	2.8 / .18	L 1
Character of Attitude Command (1.75 lb step)	Very good attitude command, peaks in about 2.0 sec and holds. Translational accel tends to zero within 12 sec.	L 1	Good AC: peaks in about 1.5 sec, then slowly decays, but translational acceleration tends to zero.	L 1
Cross coupling (Pitch/roll at 4.0 sec)	0.25	L 1	0.4	L 2
Gearing (attitude deg/lb stick at 4.0 sec)	5		1.0	
Roll response to displacement				
Bandwidth ω_{BW} / τ_P	4.5 / 0.09	L 1	3.7 / 0.11	L 1
Character of Attitude Command (0.35 in step)	Quite good attitude command, peaks at 2 sec then slowly decays, translational acceleration is decaying. Translational accel roughly constant for larger input.	L 1	Not good: peaks at about 3 sec reverses sharply to larger peak negative at 13 sec. Translational acceleration decreases till 8 sec, then increases again.	L2
Cross coupling (Pitch/roll at 4.0 sec)	0.4 to 0.23	L 1 to L2	0.5 to 0.3	L 2
Gearing (attitude deg/inch stick at 4.0 sec)	8 to 13		16 to 25	

Table 4: Handling qualities ratings for rated runs – night

ACCELERATION AND DECELERATION

Pilot	UH60		SP1A		SP3A		SP4A		SP4B		RCON6		RCON9	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A	3^4 2^ 3*	3.0	3^ 3^	3.0	4 2.5^ 7*	3.3	2.5^	2.5	2.5 3*	2.5	3^	3.0	2.5 2.5*	2.5
Ga	2 3	2.5	4	4.0	1.5	1.5					5	5.0		
Gr	4 3	3.5							3.0	3.0	4*			
H														
T	3 4 3^	3.3	2	2.0	3 3 2^ 5* 3^ 3^ 3^	2.8	2^	2.0			2 3^	2.5	3 3^	3.0
W	2	2.0			3 2	2.5					4	4.0	6	6.0
S	3	3.0	4	4.0	4	4.0			4 5 5†† 4 3†††	4.3	4**	4.0	5**	5.0
Ave		**2.9**		**3.3**		**2.8**		**2.3**		**3.3**		**3.7**		**4.1**

HOVER

Pilot	UH60		SP1A		SP3A		SP4A		SP4B		RCON6		RCON9	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A	4.5 4.5 6*	4.5	4 3	3.5	4 4 5* 7* 2	3.3	3	3.0	2.5	2.5	4.5*		6*	
Ga					4	4.0					_7			
Gr	5	5.0	4	4.0			4	4.0	4.5 4 3 3 4.5††† 3 4 4††††	3.8	4**	4.0	6	6.0
H	5 4 4	4.3	3	3.0	4 4	4.0			5.5 5†††	5.3				
T	4 5 5	4.7	5	5.0	5 5 5 5	5.0	6	6.0			5	5.0	5	5.0
W	6* 6*		3	3.0	2 3*	2.0					5	5.0		
S	4	4.0	4	4.0			5	5.0	4 4 5 5†††	4.5	4**	4.0	7**	7.0
Ave		**4.5**		**3.8**		**3.7**		**4.5**		**4.0**		**4.5**		**6.0**

SIDESTEP

Pilot	UH60		SP1A		SP3A		SP4A		SP4B		RCON6		RCON9	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A	5 4.5 3*	4.8	3 3 4*	3.0	4 3 4	3.7	3 2	2.5	3.0	3.0	4.5 4*	4.5	4.5	4.5
Ga														
Gr	4.5	4.5	4.5	4.5	4.5	4.5			3 3†††† 4††††*	3.0	3**	3.0	4.5* 5** 5.5*	5.0
H	4.5	4.5	4.5 4	4.3	4.5	4.5								
T	4	4.0			5	5.0								
W	7 6*	7.0			5 6*	5.0					_7		6	6.0
S	2	2.0	4	4.0	4	4.0			4.0	4.0	.			
Ave		**4.5**		**4.0**		**4.4**		**2.5**		**3.3**		**3.8**		**5.2**

Table 4 continued.

Rating Averages - NIGHT														
	UH60		**SP1A**		**SP3A**		**SP4A**		**SP4B**		**RCON6**		**RCON9**	
	Ht Hold		Ht Hold		Ht Hold		Ht Hold		Ht Hold		Ht Hold		Ht Hold	
	Off	On	Off	On	Off	On	Off	On	Off	On	Off	On	Off	On
Accel-decel	3.0	2.9		3.3	6.0	2.8		2.3	3.0	3.3	4.0	3.7	2.5	4.1
Hover	6.0	4.5		3.8	5.0	3.7		4.5		4.0	4.5	4.5	6.0	6.0
Sidestep	4.5	4.5	4.0	4.0	6.0	4.4		2.5	4.0	3.3	4.0	3.8	5.0	5.2

Symbols used to distinguish configuration modifications:

* Height hold off
** Reworked Height hold for the PAFCA configurations
^ Relaxed lateral standards desired to adequate

Stick force characteristics	Pitch		Roll	
	Breakout lb	Gradient lb/in	Breakout lb	Gradient lb/in
Standard	0.9	0.7	1.0	1.0
††	0.9	1.5	1.0	1.0
†††	1.0	1.0	1.0	1.0
††††	1.0	0.7	1.0	0.7

Table 5: Handling qualities ratings for rated runs - day

ACCELERATION-DECELERATION														
Pilot	**UH60**		**SP1A**		**SP3A**		**SP4A**		**SP4B**		**RCON6**		**RCON9**	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A	3	3.0	3	3.0	2.5 7*	2.5								
Ga	2	2.0			1.5	1.5								
Gr	3	3.0									3	3.0		
H														
T	3 3	3.0	3	3.0	3	3.0								
W	3	3.0												
S	4	4.0												
Average		**3.0**		**3.0**		**2.3**						**3.0**		
HOVER														
Pilot	**UH60**		**SP1A**		**SP3A**		**SP4A**		**SP4B**		**RCON6**		**RCON9**	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A	4 3	3.5	3	3.0	3 2	2.5								
Ga	4 5 4	4.3												
Gr	3													
H														
T	5 4 3	4.0	3	3.0	4 2	3.0								
W	4 6	5.0												
S	2	2.0			1	1.0			2.0	2.0				
Average		**3.8**		**3.0**		**2.2**				**2.0**				
SIDESTEP														
Pilot	**UH60**		**SP1A**		**SP3A**		**SP4A**		**SP4B**		**RCON6**		**RCON9**	
	HQR	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**	**HQR**	**Ave**
A					5	5.0								
Ga	3	3.0												
Gr	3 3	3.0												
H														
T	4	4.0												
W	4	4.0												
S	2	2.0												
Average		**3.2**				**5.0**								

Rating Averages - Day HH On

	UH-60		**SP1A**		**SP3A**		**SP4A**		**SP4B**		**RCON6**		**RCON9**	
Accel-decel		3.0		3.0		2.3						3.0		
Hover		3.8		3.0		2.2				2.0				
Sidestep		3.2				5.0								

APPENDIX A. ADS-33D-PRF CRITERIA FOR GOOD ACAH

The following paragraphs taken from ADS-33D-PRF Ref. 1, contain the criteria specified to meet the definition of Attitude Hold and Attitude Command:

3.2.6 Character of Attitude Hold and Heading Hold Response-Types. If Attitude Hold or Heading (Direction) Hold is specified as a required Response-Type in Paragraph 3.2.2, the pitch attitude shall return to within ±10 percent of the peak excursion, following a pulse input, in less than 20 seconds for UCE=1, and in less than 10 seconds for UCE>1, as illustrated in Figure A 1. Roll attitude and heading shall always return to within 10 percent of peak in less than 10 seconds. The peak attitude excursions for this test shall vary from barely perceptible to at least 10 degrees. The attitude or heading shall remain within the specified 10 percent for at least 30 seconds for Level 1. The pulse input shall be inserted directly into the control actuator, unless it can be demonstrated that a pulse cockpit controller input will produce the same response.

For Heading Hold, following a release of the directional controller the rotorcraft shall capture the reference heading within 10 percent of the yaw rate at release. In no case shall a divergence result due to activation of the Heading Hold mode.

3.2.7 Character of Attitude Command Response-Types. If Attitude Command is specified as a required Response-Type in Paragraph 3.2.2, a step cockpit pitch (roll) controller force input shall produce a proportional pitch (roll) attitude change within 6 seconds. The attitude shall remain essentially constant between 6 and 12 seconds following the step input. However, the pitch (roll) attitude may vary between 6 and 12 seconds following the input, if the resulting ground-referenced translational longitudinal (lateral) acceleration is constant, or its absolute value is asymptotically decreasing towards a constant. A separate trim control must be supplied to allow the pilot to null the cockpit controller forces at any achievable steady attitude.

APPENDIX B. EVALUATION TASKS

Hover

Objectives

Check ability to transition from translating flight to a stabilized hover with precision and a reasonable amount of aggressiveness in the DVE.

Check ability to maintain precise position, heading, and altitude in the DVE.

Description of maneuver

Initiate the maneuver at a ground speed of between 6 and 10 knots with the target hover point oriented approximately 45 degrees relative to the heading of the rotorcraft. The target hover point is a repeatable, unchanging ground-referenced point from which rotorcraft deviations are measured. The ground track should be such that the rotorcraft will arrive over the target hover point (see illustration in "description of test course")

Description of test course

The suggested test course for this maneuver is shown in Fig B1. Note that the hover altitude depends on the height of the hover sight, and the distance between that symbol, the hover target, and the helicopter. These dimensions may be adjusted to achieve a desired hover altitude. The hover target will have to be modified from Fig B1 to reflect the increased altitude tolerances allowed for the DVE.

Desired performance

Accomplish the transition to hover in one smooth maneuver. It is not acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position. Attain a stabilized hover within 10 seconds of the initiation of deceleration.

Maintain a stabilized hover for at least 30 seconds.

Maintain the longitudinal and lateral position within ±3 ft of a point on the ground and altitude within ±2 ft. Keeping the hover sight within the desired box on the modified hover target will insure desired lateral and vertical performance.

Maintain heading within ±5 degrees.

There shall be no objectionable oscillations in any axis either during the stabilized hover, or the transition to hover.

Adequate performance

Accomplish the transition to hover in one smooth maneuver. It is not acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position. Attain a stabilized hover within 20 seconds of the initiation of deceleration.

Maintain a stabilized hover for at least 30 seconds.

Maintain the longitudinal and lateral position within ±8 ft of a point on the ground and altitude within ±4 ft. Keeping the hover sight within the adequate box on the modified hover target will insure adequate lateral and vertical performance.

Maintain heading within ±10 degrees.

Acceleration and deceleration

Objectives

Check pitch axis and heave axis handling qualities for reasonably aggressive maneuvering in the DVE.

Check for undesirable coupling between the longitudinal and lateral-directional axes while performing reasonably aggressive longitudinal axis maneuvers in the DVE.

Check for harmony between the heave axis and pitch axis controllers while maneuvering in the DVE.

Check for adequate rotor response to moderately aggressive collective inputs.

Check for overly complex power management requirements while maneuvering in the DVE.

Description of maneuver

Starting from a stabilized hover, accelerate to a ground speed of at least 50 knots, and immediately decelerate to hover over a defined point. The maximum nose-down attitude should occur immediately after initiating the maneuver, and the peak nose-up pitch attitude should occur just before reaching the final stabilized hover.

Description of test course

The test course shall consist of a reference line on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the starting point and endpoint of the maneuver. The distance from the starting point to the final stabilized hover position is a function of the performance of the rotorcraft, and shall be determined based on trial runs consisting of accelerations to the target airspeed, and decelerations to hover as described above. The course should also include reference lines or markers parallel to the course centerline to allow the pilot and observers to perceive desired and adequate lateral tracking performance. A suggested test course for this maneuver is shown in Fig B2.

Desired performance

Complete the maneuver over the reference point at the end of the course. The longitudinal tolerance on the final hover position is plus zero and minus a distance equal to one half of the overall length of the helicopter (positive forward).

Maintain altitude below 50 ft.

Maintain lateral track within ±10 ft.

Maintain heading within ±10 degrees.

Achieve pitch attitude changes from the hover attitude of at least 12 degrees nose-down for the acceleration and at least 15 degrees nose-up for the deceleration. Significant increases in power are not allowable until just before the final stabilized hover.

Rotor RPM shall remain within the limits of the Operational Flight Envelope without undue pilot compensation.

Adequate performance

Complete the maneuver over the reference point at the end of the course. The longitudinal tolerance on the final hover position is plus zero and minus a distance equal to the overall length of the rotorcraft (positive forward).

Maintain altitude below 70 ft and clear of the ground.

Maintain lateral track within ±20 ft.

Maintain heading within ±20 degrees.

Achieve a nose-down pitch attitude of at least 7 degrees below the hover attitude during the acceleration and a nose-up attitude of at least 10 degrees above the hover attitude for the deceleration. Significant increases in power are not allowable until just before the final stabilized hover.

Rotor RPM shall remain within the limits of the Service Flight Envelope.

Sidestep

Objectives

Check lateral-directional handling qualities for reasonably aggressive lateral maneuvering in the DVE.

Check for objectionable inter-axis coupling while maneuvering in the DVE.

Check ability to coordinate bank angle and collective to hold constant altitude while performing moderately aggressive lateral maneuvering in the DVE.

Description of maneuver

Starting from a stabilized hover with the longitudinal axis of the rotorcraft oriented 90 degrees to a reference line marked on the ground, initiate a lateral translation to approximately 17 knots, holding altitude constant with power. This shall be followed by a deceleration to laterally reposition the aircraft to a spot 400 ft down the course within a specified time. The acceleration and deceleration phases shall be accomplished in a single smooth maneuver. The rotorcraft must be brought to within + 10 ft. of the endpoint during the deceleration, terminating in a stable hover within this band. Overshooting is permitted during the deceleration, but will show up as a time penalty when the pilot moves back within the ±10 ft. of the endpoint. Establish and maintain a stabilized hover for 5 seconds. The maneuver should be performed in both directions.

Description of test course

The test course shall consist of any reference line or markers on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the starting and endpoint of the maneuver. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance. A suggested course using traffic cones and flat markers is shown in Fig B3.

Desired performance

Maintain the selected reference point on the rotorcraft within ±10 ft of the ground reference line.

Maintain altitude within ±10 ft at a selected altitude below 30 ft.

Maintain heading within ±10 degrees.

Achieve at least 20 degrees of bank angle during the acceleration and deceleration.

Achieve a stabilized hover within 10 seconds after reaching the hover point.

Adequate performance

Maintain the selected reference point on the rotorcraft within ±15 ft of the ground reference line

Maintain altitude within ±15 ft at a selected altitude below 30 ft.

Maintain heading within ±15 degrees.

Achieve at least 10 degrees of bank angle during the acceleration and deceleration.

Achieve a stabilized hover within 20 seconds after reaching the hover point

APPENDIX C. PILOT QUESTIONNAIRE

1. Were pitch, roll, and yaw attitudes and height responses to control inputs predictable?
2. Were position and velocity responses to attitude changes predictable?
3. Did undesirable oscillations occur?
4. If trying for desired performance resulted in unacceptable oscillations, did decreasing your goal to adequate or worse performance alleviate the problem?
5. If applicable, describe any unique pilot technique that you found necessary to accomplish the task.
6. Did motion cueing seem reasonable? Any tendency for disorientation, vertigo, or feeling of malaise due to motion?
7. Assign HQR, then answer following questions.
8. If assigned HQR is Level 2, briefly summarize the deficiencies that make achieving desired performance of this task unlikely.
9. If assigned HQR is Level 3, briefly summarize the deficiencies that make achieving even adequate performance of this task unlikely.
10. If assigned rating is worse than Level 3, briefly summarize why attempting to do the task with completely relaxed performance standards puts controllability into doubt.

APPENDIX D: PILOT COMMENTS FOR HEIGHT HOLD ON

The following tables contain abstracts from the transcribed pilot comments that were guided by the pilot questionnaire given in Appendix C.

Pilot comments for configuration SP1A

Pilot	Evaluation Task		
	Acceleration-Deceleration	Hover	Sidestep
A	Run 973-976 Pitch was not very predictable ...it would bob down and then bob back up to a new heading.. So there was a second input required at the decel and the accel to initiate and terminate maneuvers, which caused a little more activity in the roll axis while trying to focus on obtaining the right pitch attitude. HQR 3	Run 1031-1035 unique pilot technique... Largely when I got into the zone.. I may have been at the top of the desired box or the bottom, once I get stabilized in the hover it was very easy to maintain wherever I was .., so I just eased off on the controls and monitored drift, .. it was very easy to eliminate drift in both roll and in lateral and longitudinal directions. HQR 3	Run 1136-1040 Undesirable oscillations? In the flare at the end there is ... there is some control feedback (which) interacts there and when that stopped there was an oscillation in roll that stayed for approximately three or four overshoots until you kind of eased off a little bit and got out of the loop and then it would settle down. If you stayed out of the loop, ... or you decreased the severity of the maneuver,..a little less roll angle to recover and not as abrupt, the oscillation was removed and it wasn't apparent. HQR 3
Ga			
Gr		1415-1424 An obvious improvement when I went from the last one (UH-60) to the very first task on this one. First try on this control system. ...And it was improved response. HQR 4	1302-1316 this configuration, I think, is a good one. I didn't see anything wrong with the configuration, .. I didn't feel any saturation or any unpredictable responses. And I still was unable to consistently perform within the desired or certainly not in level 1. But I think the response to the pilot inputs is good. A lot of my problem is in, ..the perception of the task where the helicopter is in state in this reduced visual environment here. HQR 4.5
H		1265-1270 HQR,... Satisfactory without improvement? I guess yes. Because I'm not too sure how to recommend improvements. ..I think I was aware of stick trim migration during the task, but it didn't seem to be anything that I couldn't cope with. HQR 3	1293-1301 there is a ..significant amount of workload, effort, associated with managing the longitudinal axis. More so almost than the lateral axis. This configuration was also pretty good at converging and stabilizing nicely at the final end point. However, it wasn't quite as good in that regard as the prior two configurations (SP3A, SP4B). ..But there seemed to be a little bit better predictability in the lateral translation. Still, there is clearly an opportunity for the pitch axis to become troublesome, and that degrades performance, consumes attention, and adds workload. HQR 4

Pilot	Acceleration-Deceleration	Hover	Sidestep
S	1510-1513 Position and velocity responses to attitude changes predictable? In the roll axis, yes, but (not pitch) I was trying to make small corrections around the hover point. I was able to do it in roll, but I wasn't able to do it in pitch as effectively, I was continually overshooting the precise location I wanted to be at. HQR 4		
T		1020-1024 Undesirable oscillations? I still managed to drive myself on a couple of these into a longitudinal PIO. And that was, as I tried to increase my aggressiveness a little bit in by moving over to the site, it was easy on the roll out to develop a pitch rock that I would start to get out of phase with it, it also started to drive me longitudinally and out of the desired zone. HQR 5	
W	481-492 There was this slight wash out of the pitch down inputs such that lowering the nose to say about 10 degrees nose low and it would want to wash out to ..about.5 degrees .. so that usually required a second input .. to maintain 10 degrees nose low. But it was still predictable, ..I knew it was going to happen, ...On the other end, during the decel, I put in an aft stick input and the nose would pitch up and it would just about continue to pitch up as long as you had that aft stick input in there. ..... so it required forward stick every time. ..So the nose up inputs were less predictable than the nose down inputs, but the compensation was absolutely minimal. HQR 3	606-615 Were position and velocity responses to attitude changes predictable? Yes, they were. It was quite easy to zero out the velocities down there at the hover. The recovery was pretty easy, I actually got a little bit aggressive a couple of times and still managed to recover pretty well. HQR 3	

Pilot comments for configuration SP3A

	Evaluation Task		
Pilot	**Acceleration-Deceleration**	**Hover**	**Sidestep**
A	Run 870-875 No undesirable oscillations, however there is a roll oscillation and at the tail end during the deceleration when the nose is pitched back down, there is about 2 or 3 overshoots before it's damped out. I would call those undesirable, but it didn't affect our ability to maintain desired performance. HQR 4	Run 1036-1040 In the deceleration portion in the pitch axes, ..a couple of times where it appeared as though I started to get into a PIO with large pitch excursions, ..., usually it was a couple of overshoots and then I was able to get it stabilized out. .. The more aggressive I was the more the tendency was in pitch to get that PIO. HQR 4	Run 1070-1076 I felt as though there was a little bit of a predictability problem in pitch. A drift would develop, I'd put in a correction, and .. I couldn't predictably take out the rate each time. HQR 4

Pilot	Acceleration-Deceleration	Hover	Sidestep
Ga	463-466 pitch and roll attitude responses to control inputs were quite predictable. Again, initial entry, good force, good force cue for pitch down attitude to minus 7 degrees and it was easy to hold that attitude during deceleration and then to retrim to a level 50 for a knot or so trim position. Position and velocity responses to attitude changes.. predictable except at the very end. After recovering from the flare the aircraft seems to always translate to the right. So I try to compensate and it required two or three pounds of left force HQR 1.5	517-522 Pitch seemed to have a definite lag in it. I would make an input, wait for a response, that is for large inputs. Roll was overly active. HQR 4	
Gr			1328-1335 I'm still having some problem in keeping the helicopter stopped in one spot here as I roll out, as far as fore and aft positioning goes.. There may be some roll into pitch coupling here that might be an issue of predictability or not.. The drift fore and aft sometimes it's obvious, sometimes it's very subtle HQR 4.5
H		626-631 Pilot technique is still the same, be aware of the stick detents, it seems to have a very good reference point for stick trim, for hover, and it's not just that reference point, but it's the small displacements against the gradient that are useful for tempering the control inputs. HQR 4 639-653 Slight tendency for oscillations. However, it seemed to be pretty robust for the abuse kind of situations. I wouldn't say that they are undesirable oscillations. There is a tendency to draw you into the loop with high gain and hence in the process reduce your comfort or your confidence that you are going to get the response that you are needing. Still very strong attention to the stick force breakout level as well as the force gradient. No perceptible motion of the trim actuator underneath my inputs... just kind of an overall poor predictability associated with the control inputs. HQR 4	1286-1292 Good convergence at the termination of the maneuver in the hover with good predictability .. the lateral translation is, sometimes quite well behaved .. roll and lateral velocity predictability and even .. pitch and the longitudinal velocity predictability. But on occasion it can be borderline oscillatory, unpredictable roll, and pitch response developing. With the pitch workload.. being greater than the .. lateral... So nonlinear behavior that results in a pretty good configuration as long as you don't excite some of the undesirable characteristics HQR 4.5

Pilot	Acceleration-Deceleration	Hover	Sidestep
S	1514-1516 Were pitch, roll attitudes responses to control inputs predictable? Yes. I'd say they were. The attitudes were predictable, though during the decel there were several, especially the last maneuver which I got a little slight PIO in pitch, HQR 4		
T	941-945 Position and velocity responses to attitude changes predictable? Yes. Except at the final end of the flare. It's almost like stopping and then kind of dropping. HQR 3	1006-1011 pitch and roll responses to control inputs predictable? Yes .. There still is a tendency to longitudinally PIO. Once established in a trim position, which it just took a while to get to, I think I could fairly reliably stay there, HQR 5	
W	493-502 pitch and roll attitude responses to control inputs predictable? Yes.. very predictable. It required a minimum of compensation, usually the nose down input required a second input to maintain the nose down attitude. Pretty minor input HQR 2	523-533 pitch and roll responses to control inputs were predictable. I didn't see any noticeable overshoots. ..it looked like, generally like a first order response with a pretty short time constant .. It required the pilot to kind of minimize the control inputs, the amplitude while -- during this task. And it required a little bit of backing out of the loop, but it was extremely stable once established in the hover HQR 2	534-544 The roll and the yaw attitudes were definitely predictable. No problems there. The pitch was not always predictable. sometimes it required .. large amplitude pitch inputs in order to maintain center line. It was really quite difficult to maintain X position during the course of the maneuver. In order to do so, you had to anticipate the need for longitudinal inputs. When you didn't anticipate it, if you got behind, then you could make all the longitudinal inputs you wanted and you wouldn't get any response at all. HQR 5

Pilot comments for configuration SP4A

Pilot	Evaluation Task		
	Acceleration-Deceleration	Hover	Sidestep
A	Run 965-968 The biggest thing I want to describe here is ..the first time I did this maneuver, it felt as though the aircraft was almost springy or spongy. .. this was the first time I have noticed control feedback in the stick. ..as I put the nose down 12, 15 degrees for the acceleration, I could do it precisely, but I had to get used to feeling a strong back force in the stick. The back driving of that stick was very noticeable in this configuration. And when I went forward for the decel, the same was true .. It felt like more stick force in my hand. The last couple of times, though, it actually seemed crisper once I realized it was in my hand, because I could control the force and I wasn't trying to fight it to get it back to a position. We don't	Run 1041-1046 There was an oscillation in the roll in a couple of these.. it appeared as though I got into a little oscillation where it just constantly rocked and rolled in a couple of the maneuvers. HQR 3	Run 1081-1086 pilot compensation wasn't a factor in achieving desired performance. There were some minor corrections, very minor. . at both ends. In fact during the decel .. put in the decel, bring it back to level, take out a couple of drift corrections and then it would stay right there... My initial feeling on this one in the first couple times I flew it was the aircraft felt sluggish, very heavily damped .. that was the feeling initially until I started letting the aircraft do its own thing. HQR 2 1143-1149 Pitch, roll and yaw attitude responses to control inputs were predictable. However, in the roll axis there was significant amount of force feedback, especially in the initial input to the 20 degrees. So

	typically fly force in helicopters, but that cueing is an indication that the stick is moving when it's really just a force. It hasn't moved any displacement. ... the pilot technique was to .. set a stick displacement and hold it there and just hold the force cue, hold the force cue there and it seemed to hold it real tight. The only pilot compensation that is required is to resist that stick force, really, so there is some pilot compensation required for this task in the fore and aft direction. HQR 2.5		substantial that it affected my ability to manage the pitch responses because the lateral force feedback was very strong. If you try to go to a lower level of performance, down at the other end, or ease off, the oscillation goes away. It's really not a function of the tolerance, it's a function of how much the pilot feeds back. Left to its own, the stick by itself, maybe with one slight overshoot, it would settle out to a stable hover position. HQR 3
Pilot	**Acceleration-Deceleration**	**Hover**	**Sidestep**
Ga			
Gr		1469-1475 This is what I consider one of the better configurations. I wasn't quite concerned about the force gradients this time, .. the flight control system and the force gradients were closer in harmony with each other. So this was a pretty good configuration. It's characterized by kind of a low frequency, lower bandwidth type of response. I didn't feel any bobble and over control on my part. I didn't have to tell myself to keep backing off. And it looked pretty good. HQR 4	
H			
S		1401-1403 Pitch and roll responses to control inputs predictable? . okay in roll. But I didn't like the pitch axis.. there was a lot of over controlling going on, so it wasn't as predictable as I have seen. HQR 5	
T	962-964 Good, negligible deficiencies. Pilot compensation not a factor for desired performance. The pitch and roll, very harmonious. And while not as heavily damped as some in the roll axis, it just was a nice combination and seemed to fly well. .. I know from looking at that stick plot .. it's moving around a lot. It sure didn't seem like a lot of work. So, I don't know whether that's deceiving or what, it might have moved, but it really wasn't a lot of compensation. HQR 2	999-1005 no comments on force from the trim .. back through the cyclic, .. nothing there was objectionable. But there was a definite tendency to launch into a pitch oscillation at the higher work loads, even though when you look at the (control position) plot it doesn't look like the stick is moving that much. HQR 6	
W			

Pilot comments for configuration SP4B

Pilot	Evaluation Task		
	Acceleration-Deceleration	**Hover**	**Sidestep**
A	Run 1255-1259 Did undesired oscillations occur? The roll axis seemed very lightly damped and any corrections down the track in the roll resulted in a couple of oscillations. It felt relatively loose in roll, at least as we were headed down the track. It didn't appear to show up very much in the decel at the other end. HQR 2.5	Run 1226-1231 it seemed to be very comfortable capturing the hover position and then some small corrections to zero out the rates, then it seemed very stable ... it achieved stability very quickly and required little compensation after that. HQR 2.5	Run 1096-1102 Undesirable oscillations did occur. .. down at the recovery end, you feel the lateral stick, trying to achieve the trim condition and if you resist that input, it results in a PIO ... I got into it the first two times that I did the maneuver and then this last run I tried to repeat it and that's exactly what happened. If the stick is allowed to do its thing, it settles out very nicely in the roll axis, but the slightest, just a small interaction by the pilot to stop that stick movement results in undesirable oscillation. So by letting it go a little bit and trying to accept the lower level of performance .. and staying off the stick, the oscillation went away. HQR 3
Ga			
Gr	1488-1493 This configuration is another good one. I thought I felt a little bit of backdrive on the longitudinal cyclic once or twice, but nothing that bothered me at all. I just sensed it, but I didn't sense it consistently HQR 3	1425-1433 I did okay at first, but as I look at the traces, .. the helicopter is just drifting fore and aft and I'm not picking up those drifts until it's too late. I put in a response, but I don't get a good response in attitude from the control system. So .. there is kind of a sluggishness. HQR 4.5 1458-1464 some general comments.. it seems like a lot of the difficulty in the task in trying to stabilize this precisely is a function quite a bit of the force characteristics ..The detent, the breakout force and the force gradients around zero. .. I would say if those could be lightened up, I would probably do better. HQR 4 1565-1569 This was obviously a good configuration here. .. I saw little tendency to overcontrol, even though I sometimes got into a tight loop...Once I got into the box I was able to take my hands off the controls and just let it sit there HQR 3	1317-1327 I noted early in the runs here an improved, lateral response, feels like a higher bandwidth in the roll axis. Entirely predictable...I like this configuration, this roll configuration better than the previous one (SP1A) .. I was able to perform a little bit better, a bit more consistently, as far as trying to stay within the desired standards. .. I saw nothing that was a problem and it's just, getting used to the goggles and the reduced visual environment HQR 3.
H		1271-1274 Poor predictability in pitch and roll. I must be closing inner loop strongly on stick force today. And secondarily stick position, but clearly somebody else is moving the controls in addition to me and in a way that I cannot adapt to, and so it eliminates or removes a lot of predictability from the task, results in oscillatory	1275-1285 characteristics tend to be difficult and oscillatory in both axes, especially the pitch axis during the translation, but they converge nicely on stable hover... it's kind of an odd behavior, where the stabilization features are good or its convergence to the hover are good, but the maneuvering excites undesirable

		characteristics and demands a lot of attention. I think this is an example where force feedback as part of the inner loop mechanism is disruptive in trying to accomplish the task. I had to think a lot of exactly where the control is. That is, open up the control position feedback loops and accentuate the control force feedback loops ..Also I had to pay a fair amount of attention visually and cognitively to observe the pitch attitude as a way of leading the velocity and position responses I was trying to get. The pitch and roll responses were predictable, but they seemed to be of relatively low bandwidth.. So overall lots of things demanded attention over and above the task objectives. HQR 5.5	characteristics....backing out of the loop seemed to be effective for arriving at the hover point. But on another occasion I tried to back out of the loop immediately after initiating the maneuver, and the aircraft went more divergent in pitch, so there is some confusing behavior HQR 6
Pilot	**Acceleration-Deceleration**	**Hover**	**Sidestep**
S	1507-1509 I have seen better, but overall predictable. I didn't like the roll, ... too bobbly from the outset, the very first acceleration. It was jiggling around a lot on the first decel, I'm sure I was rolling plus or minus 5 degrees or so, and that was uncharacteristic of the maneuvers that I have done HQR 4 1517-1519 I didn't find the velocity response too difficult or too unpredictable in pitch or in roll. I was able to capture a velocity fairly easily, I was able to target velocity at 50 to 55 knots. And I was able to get that no problem. But the position responses in both pitch and roll I didn't like at all, especially at a hover. .. HQR 5	1396-1400 Pitch and roll responses to control predictable? Yeah, but I didn't like the pitch axis... there were several times when I wasn't able to predict exactly -- I wasn't able to put the aircraft exactly where I wanted. Same for the position and velocity responses .. for instance, in that last run. I was drifting aft, I knew it, I tried to correct it and didn't correct it in time to keep it within desirable. So in that case the position and velocity or in this case position response to attitude changes wasn't predictable. HQR 4	1446-1449 summarizing the deficiencies that make achieving desired performance of the task unlikely. I would say that the deficiencies are ... it's just a little too lively in roll and I'm afraid to say pitch. The last maneuver I didn't really see any oscillations in pitch, but it seemed more difficult to maintain a good fore and aft position. So I would say it's a little bit too lively laterally and perhaps as well in the pitch axis. HQR 4
T			
W			

Pilot comments for configuration UH-60 (with Height Hold)

	Evaluation Task		
Pilot	Acceleration-Deceleration	Hover	Sidestep
A	Run 864-869 Desired performance requires a moderate pilot workload. It's mostly in the end, staying within the band.. I tried to ease off a little bit, if the nose gets up beyond where I can see the horizon, it's just those lines, then it takes a moderate compensation to stay even	Run 759-765 Position and velocity responses to attitude changes were predictable. .. some discontinuity between the predictability in roll and pitch. Longitudinal seems to be more predictable, but the focus had to be on left and right drift, which would take your attention away from the fore and aft. HQR 4.5 1025-1030 position and velocity responses	Run 813-819 ..position and velocity responses to attitude changes predictable? Not the longitudinal at the decel end. Did undesirable oscillations occur? Yes, in the pitch axis you get a lot of fore and aft pitching going on in the final portion of the decel. HQR 5

	within adequate tolerance. HQR 4.	to attitude changes predictable? I think this is where I had a problem The velocity cues would pick up and .. if you were distracted for a moment from one of the axes, it was very difficult to know exactly how much you were putting in Every time you made a control input you had to monitor what happened to predict how much attitude and velocity you were getting for that particular input. HQR 4.5	1060-1069. attitude responses to control inputs predictable? I had a little bit of predictability problem in the fore and aft, I couldn't judge exactly how much was required to get rid of the rate ..and unless I was monitoring it pretty well, it caused me to go outside the adequate bands. HQR 4.5
Pilot	**Acceleration-Deceleration**	**Hover**	**Sidestep**
Ga	474-480 pitch and roll responses to control predictable? Yes. I was able to get aggressive on entry. .. for some reason I had more trouble controlling the roll out from the flare. I should say the recovery to the hover attitude always seemed to fall through and require another correction to come to the hover attitude. ..at least two corrections were required. More difficult than previous configurations, (SP1A, SP3A) reacquiring the hover attitude at the far end HQR 2	412-417 Pitch and roll attitude and height responses to control inputs predictable? In this case I had much more oscillation laterally in trying to hold the hover point than in other configurations. I seemed to have a constant low amplitude roll oscillation, not even measurable attitude change, a constant, probably 2 hertz, lateral oscillation. Pitch attitude did seem to have a lag. If you try to put in an attitude change to correct a drift, there seemed to be a slight delay, so I would over compensate with longitudinal input. HQR 5.	
Gr	1483-1487 It's been a little while since I've looked at this particular task, and it's probably the easiest of the three. The problem that I was consistently experiencing here was one of perception of the lateral track during the flare .. If you do a high nose up flare as required, you lose reference to things on the ground. And the helicopter will move sideways ...Another problem I was experiencing was being too aggressive on the decel flare and not getting the nose pitched over in time to keep from drifting aft. Again, that's a perception problem, not being able to see the drift until the pitch attitude was down. So those are all night vision goggle perception things and of course do affect the pilot's performance. But this was a good configuration. HQR 3	1404-1414 Some preliminary comments. I haven't done this hover task in a while, but I recall it was probably the hardest of the three.. I found that I was really over controlling in sort of a high frequency kind of a dither and I had to keep telling myself stop doing that. .. without motion I wouldn't have picked any of that up. But here I could feel it and I think I was responding to it in an over control mode .. my best performance is when I said stop doing that and tried to let the stabilization system in the airplane .. stabilize it there. A couple of times I came in rather quickly and did a rather abrupt decel and of course, I just lost it HQR 5	122-129 did undesirable oscillations occur? The only thing I saw was I was pumping the stick a little bit a couple of times, trying to stabilize the helicopter in the final hover position. And again, I think the reason why I'm putting in those kind of abrupt inputs was I was unable to perceive the drift or my position error until it built up quite a bit. Then I whapped in a lot of input. So again, that's that predictability thing, due to the degraded visual conditions here. HQR 4.5

Pilot	Acceleration-Deceleration	Hover	Sidestep
H		616-625.. the attitude responses to the control inputs were predictable. However, for the fine degree of control that's required, there is a bit of a mismatch between the breakout, which is fairly high in the stick, and the tiny adjustments in pitch and roll attitude that you are looking for. Position and velocity responses... are where I had most difficulty. Suddenly there could be a large excursion developed, simply in the .. time it took to scan right window to center window. .. in a sense it was predictable but suddenly large changes could occur that you did not expect. HQR 5 632-638 There did not seem to be the tendency for undesirable oscillations. For some reason, some clever engineering design reason, of course, the configuration seems to be pretty good, even though it seems to have this characteristic of perceptible trim motion. Again, the technique is to be very precise on pitch and roll. And I have to .. be very aware of cyclic position as a feedback. Not just force on the cyclic HQR 4 654-659 Comparing this configuration to the prior configuration (SP3A), this was better. There was more predictability in the velocity response and the attitude wasn't walking around as much. Maybe the vehicle is really pretty good. The limitations that I'm having are really visual cueing limitations, my perception of error thresholds is .. largely responsible for my poor performance. I really have to place a lot of effort to precisely line-up the pylons, and take a quick look at the chin window and kind of extrapolate where the center axis is supposed to be .. am not, real confident that I could solidly get consistent repeatable desired performance out of this thing, although the aircraft is pretty good HQR 4	1109-1124.. the whole pitch and roll axis was kind of difficult to control. There was lack of predictability. I have the feeling that it's because the trim point on the stick is moving around on me and it's confusing the force feedback with the displacement feedback on where the stick actually is. So I would have to say that ..in general I had to feel the aircraft around quite a bit and the predictability was less than desired. On the other hand, I had pretty decent success being able to control my position and velocity relative to the visual cues. And even though errors did develop, I could observe them, stop them, and correct them in a pretty predictable way with a fairly low workload. HQR 4.5
S	1502-1506 Position and velocity responses to attitude changes predictable? Yes.. Fine corrections around the hover point were easy to make and I was able to precisely control my position there. Also ..it was very easy to get 50 knots or between 50 and 55 every time without even thinking about it. ..for the lateral axis, I had a tendency to drift to the right during the initial acceleration, I don't know why .. I was able to correct, though, .. to get it back to the center line and that was very predictable HQR 3	1379-1384 Pitch, roll and yaw attitudes and height responses to control inputs predictable? Yes Position and velocity responses to attitude changes predictable? Yes. Did undesirable oscillations occur? Yes... it appeared to me that in the roll axis it was a little bit livelier than what I had seen to this point. And pitch... once I got in the loop pretty tight, I was PIOing it a little bit. In fact I think I was PIOing it more in pitch than I was in roll, HQR 4	1442-1445 Undesirable oscillations occur? Yes. As a result of the rapid decel, lateral stick input. There were a few lateral oscillations but it was fairly heavily damped and maybe one or two overshoots. Same thing in pitch, although this time it was more in roll. HQR 2

Pilot	Acceleration-Deceleration	Hover	Sidestep
T	845-849 Position and velocity responses to attitude changes predictable? Yes, by and large. .. on some of those flares I appeared to get a lot more benefit from the flare than I thought I was getting previously.. the airplane seemed to stop a lot better. So in some cases it was a little less predictable than it was earlier in the exercises HQR 3	736-740 the learning curve on this configuration seemed pretty steep...we almost attained all desired performance as opposed to just nearly adequate performance. ..position and velocity responses to attitude changes predictable? Yes. More so than the others (SP3A), although you could still see that there was a little more longitudinal workload required than in roll. HQR 4 789-792 Did undesirable oscillations occur? Yeah, there were oscillations as I would attempt to control my position longitudinally, it seemed like I would overcontrol a little bit on the nose and then that would result in the longitudinal oscillations HQR 5 797-804 Were pitch and roll responses to control inputs predictable? Roll, yes. Pitch, not as much.... I don't know if that combined with the lack of visual cues to my fore and aft position .. was causing most of the fore and aft workload, .. I would be willing to bet that most of the roll control workload was in just rolling into and then rolling out of, the maneuver. HQR 4 994-998 Position and velocity responses to attitude changes predictable? By and large yes .. both pitch and roll, appeared to be one of the more lightly damped configurations... certainly .. the airplane didn't stay where you put it very well HQR 5	
W	286-294..pitch, roll and yaw attitude and height responses to control inputs predictable? Yes, they were very predictable. There was at most a one or two degree overshoot on the initial pitch inputs. And at the very end when the aircraft was brought to a stable hover there was some real minor overshoots, maybe one degree or so. But overall they were extremely predictable. It was a real good level of control sensitivity and damping. And it was quite nice, actually. ..position and velocity responses to attitude changes predictable? Yes, they were. There was almost no compensation required. Once you made the initial control input to the nose low attitude, the aircraft responded, it maintained that attitude and the acceleration to the 50 knots was pretty consistent every time. HQR 2	556-563 pitch and roll attitude responses ... slightly less than predictable. All the inputs are extremely small and so the changes in pitch and roll attitudes are very small. However, it seemed that .. a roll input was accompanied by an oscillation... ..and since it required a lot of roll inputs because it was very difficult to stabilize, it was almost a constant oscillation. The pitch inputs seemed to take a long time to reach steady state, .. they were a little bit less than predictable. Position and velocity responses to attitude.. were unpredictable. It was extremely difficult to zero out translational velocities, especially fore and aft...they were really slow to develop. I would make an input and think that the aircraft should stabilize over a point and instead two seconds later it would be drifting aft or forward and the rate building relatively quickly. But the rates started off building very, very slowly, and so were difficult to detect.. they made it virtually impossible to stabilize over a point and to set the helicopter right over a point. HQR 6 564-573 pitch and roll attitudes and responses to control inputs were predictable. There was a slight oscillation with the roll	581-590 Pitch and roll attitudes and responses to control inputs were not totally predictable.. beginning the maneuver the roll responses was predictable. It was easy to achieve the desired roll angle. Coming out of the maneuver, decelerating, it often over shot level and would kind of roll back the other way. I would expect it to have gone back to level and stop there. But instead it would continue through level and go back into a right bank and require a couple of roll inputs in order to settle it down. So it was predictable during the entry to the maneuver, but it was less predictable once it got real dynamic.. Longitudinal was extremely difficult to predict. It required compensating for the nose up moment that occurred as you began to drift to the right ..it was extremely difficult to tell when to apply the compensation. If you applied it too early, then you drifted forward and went out

	Acceleration deceleration	Hover	Sidestep
		inputs, but it wasn't really a factor in anything, it was just barely noticeable. Were position and velocity responses to attitude changes predictable? In roll they were, longitudinally they weren't The velocity responses were real slow to build and it made it pretty difficult to zero out the fore and aft translations.. it was always fore and aft that I was getting out of the box. Laterally it wasn't too bad at all.. Most of the stabilize times were pretty long. ..the reason was the fore and aft velocities built up kind of slow, so they were difficult to detect and compensate for. HQR 6	of the bounds. And if you applied it too late.. there was almost no control response at all So pitch was extremely difficult to predict. And it required real precise timing as far as maintaining the X position. It was only the last two runs where I was able to do it. And I think that was more luck than anything. You can see on the traces that the amplitude of the control inputs longitudinally were just huge but.. the motion of the aircraft fore and aft was minimal. ..So that supports the fact it's kind of difficult to predict. HQR 7

APPENDIX E: PILOT COMMENTS FOR HEIGHT HOLD ON AND OFF.

	Pilot	Height Hold on	Height Hold off
Acceleration-deceleration			
UH-60	A	(Run 864-869) Was pitch, roll and yaw responses to control inputs predictable? Roll was very predictable. Pitch was not so, in that there appeared to be a lag. I put the control input in and then the attitude would continue to come in for a split second after the long stick had been applied. HQR 4	(Run 1250-1254) Were pitch, roll and yaw attitude responses to control inputs predictable? Yes. So were height responses. HQR 3
SP3A		(922-926) Pitch, roll and yaw attitude responses to control inputs were predictable. HQR 2	(917-921) Pitch, roll and yaw attitude responses to control inputs were predictable. The collective responses didn't appear to be.... as soon as I pitch above the horizon .. to continue to decel, I actually have no vertical motion cues whatsoever, and so I have no idea (if) I'm climbing, (or) descending, and I also have no seat of the pants cues, or at least they are not typical of the airplane, so it's very hard for height control in the very tail end (of the maneuver). ...height control is affecting also the roll control, because it's drifting to the right each and every time in the deceleration. HQR 7
	T	(904-908) Pitch and roll responses to control inputs predictable? Yes. Roll ..appeared a little bit lighter damped than the earlier ones. HQR 3	(910-915) Pitch, roll and height responses to control inputs predictable? Yes. Although at the end ...I got almost out of phase with my collective as I was trying to maintain height control. HQR 5
Hover			
UH-60	A	(1125-1135) Were position and velocity responses to attitude changes predictable? I think this is where I had a problem on this particular one. The velocity cues would pick up and there was a constant monitoring, if you were distracted for a moment from one of the axes, it was very difficult to know exactly how much (control input) you were putting. Every time you made a control input you had to monitor what happened to predict how much attitude and velocity you were getting for that particular input. HQR 4.5	(1182-1187) Did undesirable oscillations occur? .There is.very little to pick up in terms of vertical reference cues. ... only cue is that the box within the box that we are using for desired, adequate performance, ... pitching of the aircraft as you try to get rid of forward drift, results in a movement of that box, that ... is indicative of perhaps a climb ..So as soon as you go the opposite direction with pitch, now you are too high and you start into almost a PIO because of those two events.. Motion cueing, I still think that the vertical motion cues aren't what they should be to simulate the real aircraft.... but having been in the simulator for four days, are sensing a little bit more what those motion cues are and have .. adapted somewhat to the simulator cueing. HQR 6
	W	(556-563) Okay. Pitch and roll attitude responses to control inputs, are slightly less than predictable. All the inputs are extremely small and so the changes in pitch and roll attitudes are very small. However, it seemed that the roll attitude was accompanied by an oscillation or a roll input was accompanied by an oscillation. It seemed to set off an oscillation every time. And so ..because it was very difficult to stabilize, it was almost a constant oscillation .. HQR 6	(574-580) .. pitch and roll attitudes and responses to control inputs were predictable. There was a real slight oscillation with the roll inputs, but it wasn't really a factor in anything, it was just barely noticeable. .. overall they were predictable. HQR 6

Hover	Pilot	Height Hold on	Height Hold off
SP3A	A	(1036-1040) Pitch, roll and yaw attitude responses to control inputs were predictable. HQR 4 (1055-1058) Were pitch, roll and yaw attitudes and height responses to control inputs predictable? Yes. HQR 2	(1047-1054) Pitch, roll and yaw attitude responses to control inputs were predictable. But height responses to control inputs were not. HQR 7 (1188-1195) Pitch, roll and yaw attitude responses to control inputs predictable.. height responses.. still having trouble predicting exactly how much I need to take out of descent or climb rate, and depending on how fast or how quick that descent or climb is, directly affects my ability to manage the rest HQR 5
SP3A	W	(523-533) pitch and roll responses to control inputs were predictable. I didn't see any noticeable overshoots. ...it looked like a first order response with a pretty short time constant there. ....pretty responsive to control sensitivity. It required the pilot to kind of minimize the control inputs....and a little bit of backing out of the loop, but it was extremely stable once established in the hover. .. definitely predictable. And pretty nice. HQR 2	(574-580) pitch and roll attitudes and responses to control inputs were predictable. I didn't see any kind of overshoots or any kind of oscillations involved. They were very predictable and very easy to control. HQR 3
Sidestep			
UH-60	A	(1060-1069) Were pitch, roll and yaw attitude responses to control inputs predictable? I had a little bit of predictability problem in the fore and aft, I couldn't judge exactly how much was required to get rid of the rate and it caused me a couple of times to go outside of the desired band. In some cases, unless I was monitoring it pretty well, it caused me to go outside the adequate bands. Did undesirable oscillations occur? None substantially that I saw. HQR 4.5	(1232-1241) Pitch, roll and yaw attitudes and height responses to control inputs predictable? Yes. Did undesirable oscillations occur? Yes, they did in the roll axis. When you captured the task, the more aggressive the roll attitude, there tended to be an oscillation. And that oscillation was largely damped out if the pilot stayed out of it, but again, any pilot interaction with the stick resulted in some sort of roll oscillation during the capturing of the heading. And the deceleration at the other end. HQR 3
	W	(581-590) Pitch and roll attitudes and responses to control inputs were not, totally predictable. Going into the -- beginning the maneuver the roll responses was predictable. It was easy to achieve the desired roll angle. Coming out of the maneuver, decelerating, it often over shot level and would kind of roll back the other way. .. And then longitudinal was extremely difficult to predict. It required compensating for the nose up moment that occurred as you began to drift to the right...and it was extremely difficult to tell when to apply the compensation. If you applied it too early, then you drifted forward and went out of the bounds. And if you applied it too late, if the nose up pitch moment occurred -- or began, and then you applied the forward cyclic, there was almost no control response at all. ... till the very end of the maneuver. Then you would translate forward, after you had finished rolling out. So pitch was extremely difficult to predict. HQR 7	(591-599) Pitch and roll, yaw attitudes and responses to control inputs again, it was much like the last run. (see 581) They were not as predictable as they should be. Roll wasn't too bad. Roll inputs, especially starting the maneuver, accelerating, were very predictable, pretty easy to control, achieve the desired angle. And coming out of the decel and into it was also relatively easy to bring the thing to a stable hover in the roll axis. A real minor overshoot down at the end, but it would require maybe one or two compensating inputs after centering the stick. But longitudinally, again, it required a tremendous amount of work trying to keep it within the boundaries. HQR 6

Sidestep	Pilot	Height Hold on	Height Hold off
SP3A	W	(534-544) The roll and the yaw attitudes were definitely predictable. The pitch was not always predictable. ...sometimes it required huge amounts or large amplitude pitch inputs in order to maintain center line. It was really quite difficult to maintain X position during the course of the maneuver. In order to do so, you had to anticipate the need for longitudinal inputs. When you didn't anticipate it, if you got behind, then you could make all the longitudinal inputs you wanted and you wouldn't get any response at all. HQR 5	(600-605) Roll and yaw were predictable. Again, pitch was the most difficult axis. It required relatively good timing and relatively large inputs in order just to maintain X position throughout. If you got started early, then you drifted forward and if you got started late, then you got almost no control response at all. So pitch was a lot less predictable than roll during the maneuver. HQR 6

APPENDIX F: PILOT COMMENTS FOR EFFECT OF STICK FORCE CHANGES

The following summarizes the effect of stick force gradient and breakout on configuration SP4B

Definition of stick force characteristics

Force characteristics	Pitch		Roll	
	Breakout lb	Gradient lb/in	Breakout lb	Gradient lb/in
Standard	0.9	0.7	1.0	1.0
††	0.9	1.5	1.0	1.0
†††	1.0	1.0	1.0	1.0
††††	1.0	0.7	1.0	0.7

Pilot comments for configuration SP4B

Force characteristics	Evaluation Task: Acceleration-Deceleration	Evaluation Task: Hover	Evaluation Task: Sidestep
††	Pilot S, Run 1520-1523 Were pitch and roll attitude responses to control inputs predictable? Pitch I'd say yes. And roll I'd say no. I didn't like the roll axis in this configuration. I tended to overcontrol it. There were several instances where I had a hard time maintaining a precise attitude in roll, especially during the decel. So I would say pitch was okay and roll was not predictable. I didn't like the extra force gradient in the stick. I'd say that was moderately objectionable. HQR 5		
†††	Pilot S, run 1537-1541 Pitch and roll attitude responses to control.. position and velocity responses to attitude changes were predictable Did undesirable oscillations occur? Yeah, in both axes but very minimally. Primarily during the decel and stabilizing there in a hover. It seemed like there was a little bit of slop, but that was the only annoyance that there was .. the force gradient was stronger than it had been in (standard) configurations, but not as strong as it was, (in TT) So I don't know, maybe I'm just imagining all that. HQR 3	Pilot S, Run 1561-1564 Pitch and roll responses or attitude to responses in the control inputs predictable? In pitch, not so much. But in roll it was fine. I didn't like the pitch axis. Again, I was chasing it a little bit and PIOing just a little bit, especially on that last run. It seemed like the closer I was in the loop the more PIO I got, which I guess makes sense, but when I sort of just let things go on their own, they worked out a little bit better. HQR 5 Pilot Gr, Run 1570-1574 I usually make a comparison between the configurations. I had to work harder (than standard) trying to perform within the desired	

	Acceleration-Deceleration	Hover	Sidestep
		standards and still I didn't do as well. So I was having some problems trying to not only get stabilized, but once I was in the box, being able to move it around. This time I was able to take my hands completely off the controls, just for short periods of time towards the end of the 30 seconds, where on the (standard) configuration I was able to take hands off for a longer time. HQR 4.5	
††††		Pilot Gr, Run 1586-1590 General comments, this configuration was one of the better ones .. for the first few tries, I was kind of oscillating fore and aft, trying to find the attitude to keep the thing stopped here. And sort of got into a fore and aft PIO. It didn't have any kind of characteristic frequency to it, but just wandering around. So I was able to keep trying to get out of the loop completely and get my hands completely off the controls. And that actually worked for a while. So this is a pretty good configuration. HQR 4 Pilot S Run 1549-1553 Pitch and roll attitude responses to control inputs predictable? I didn't like them. Too bobbly, too loosey goosey. I think they were unpredictable. Position and velocity responses to attitude changes predictable? Same thing. I was overcontrolling initially in fore and aft, and then I was overcontrolling laterally. Just fine corrections I find myself getting in little PIOs. HQR 5	Pilot Gr. Run 1591-1596 This configuration generally is a good one. I saw nothing in the response to the aircraft as far as the predictability issues and undesirable oscillations go. Again, this task requires a lot of perception of fore and aft drift, particularly during the recovery to hover at the other end. And it's just a matter of doing that, of being of course, more difficult here with the night conditions and goggles. But I saw nothing in the control system in the way of any problems. HQR 3 Pilot Gr. Run 1597-1607 (HH off.) This again is a good configuration. And with the added task of holding altitude with practice, I was able to stay pretty much within the desired range here. A little bit more workload, of course, but the my time with the goggles and on this task, the proficiency is getting up to where I could spot changes in altitude as well as some fore and aft drift and so forth. And it looks pretty good all around. I see nothing in the flight control system that would require improvement. I saw no saturations, I saw no oscillations, I felt no stick back drive or unpredictable response and so forth. HQR 4

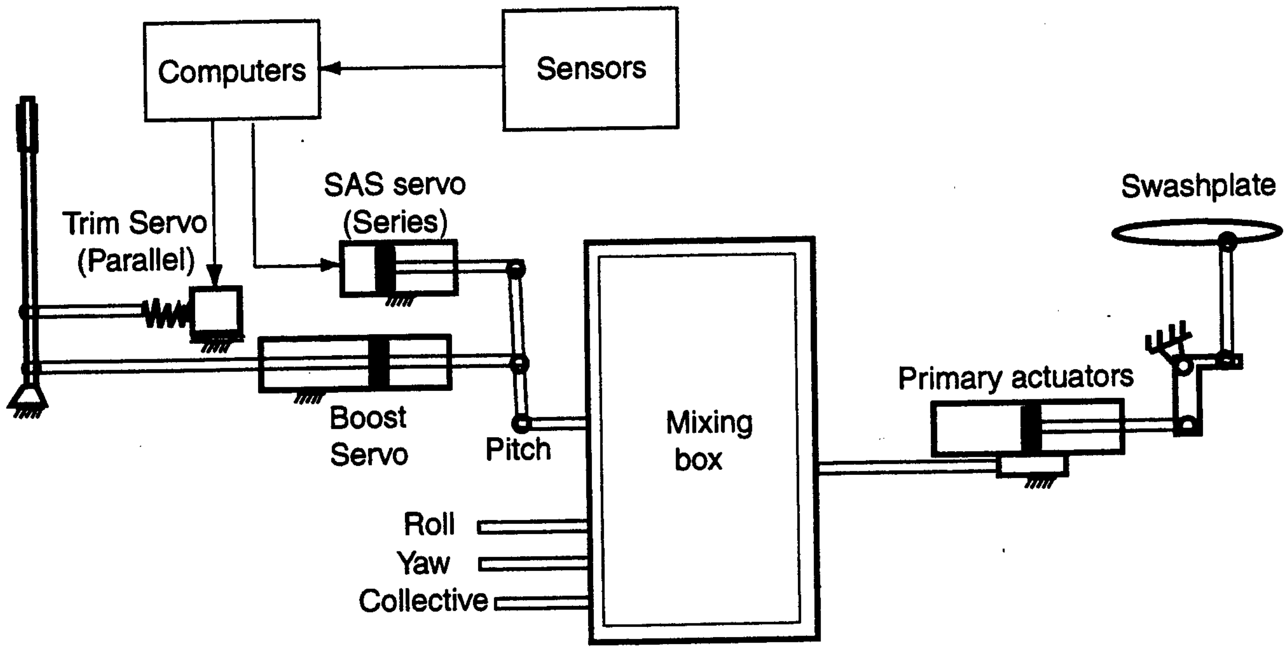


Figure 1: Functional schematic of Limited Authority SCAS

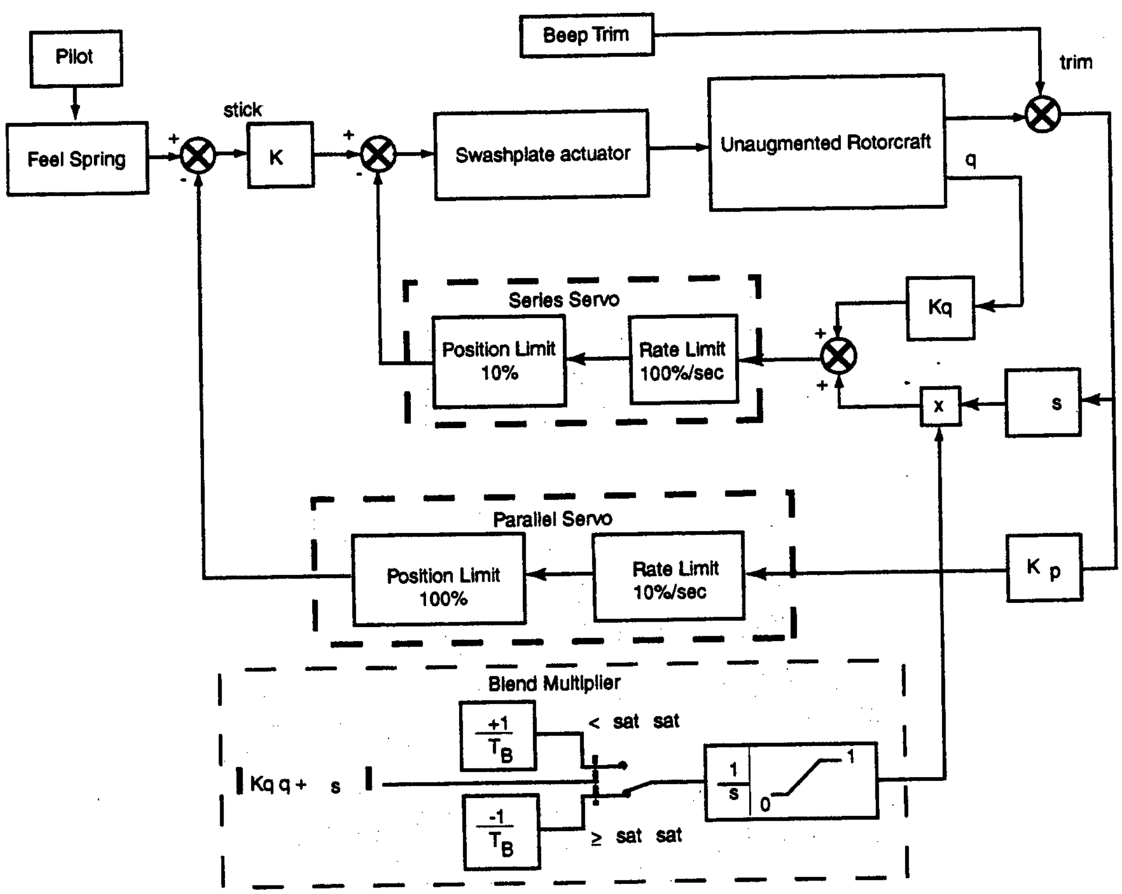


Figure 2: LASCAS control system architecture (Split Path augmentation with blend out)

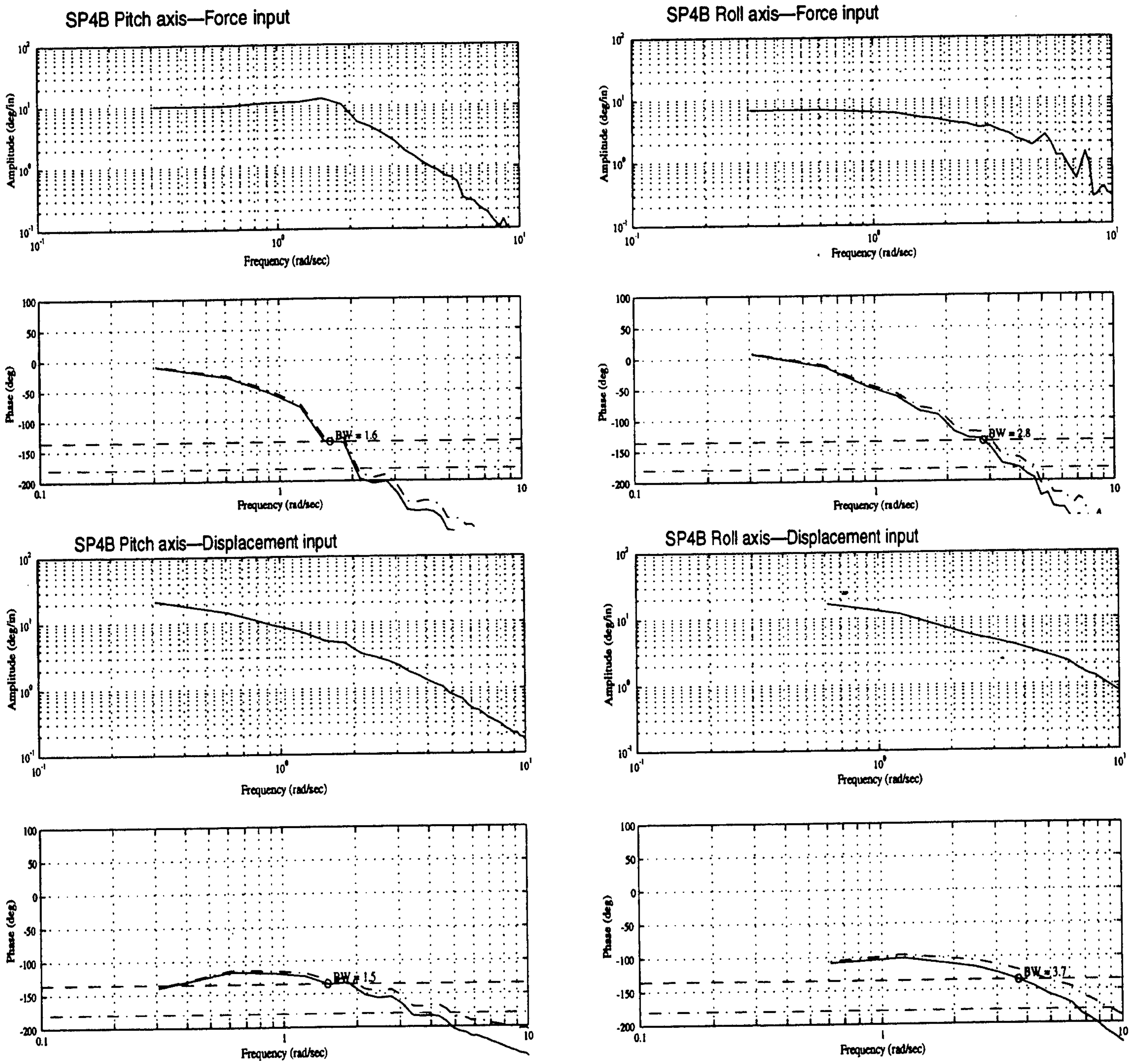
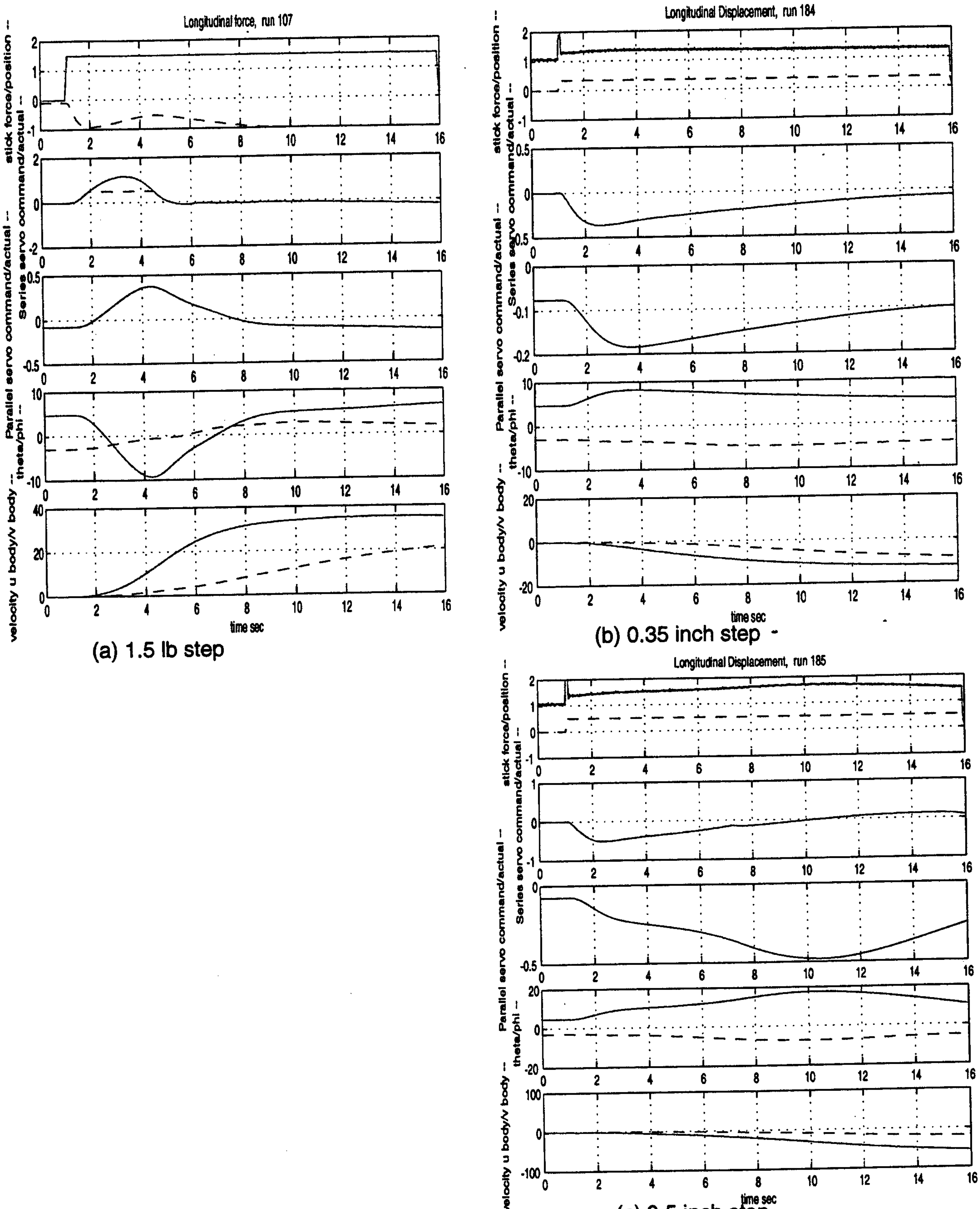


Figure 3: SP4B Bode plots (——— corrected for visual display lag, ——— uncorrected)

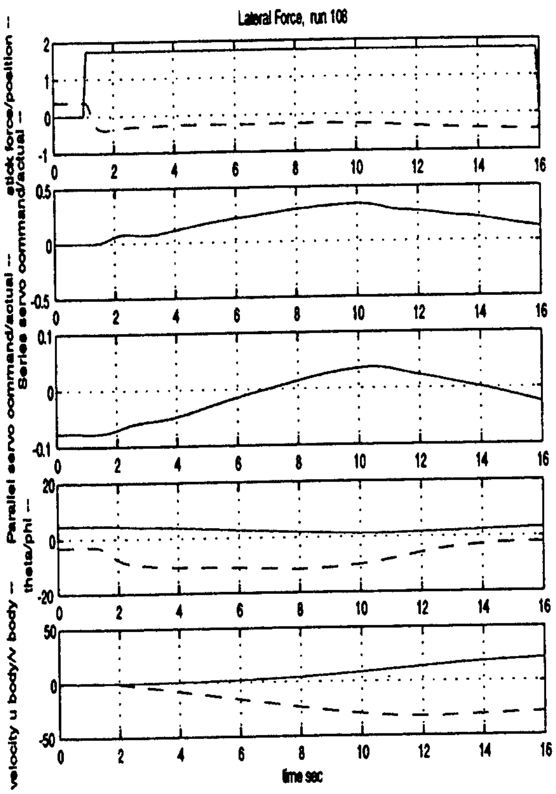


(a) 1.5 lb step

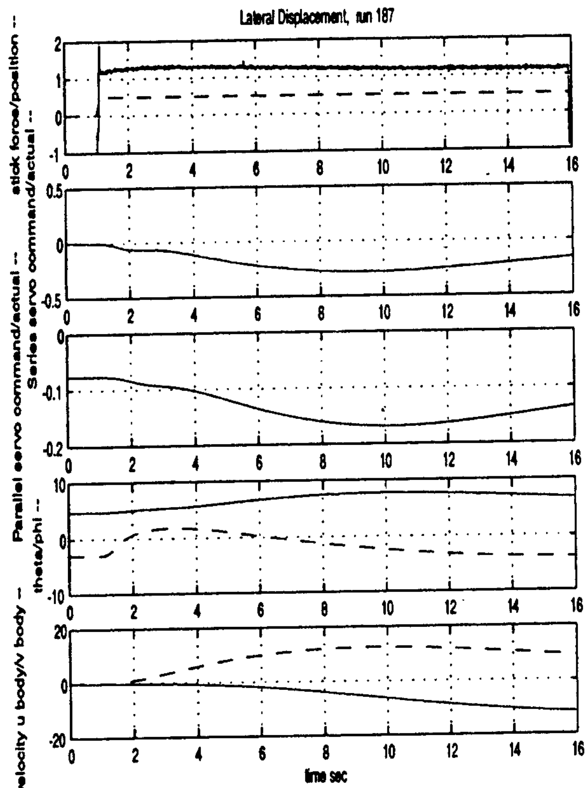
(b) 0.35 inch step

(c) 0.5 inch step

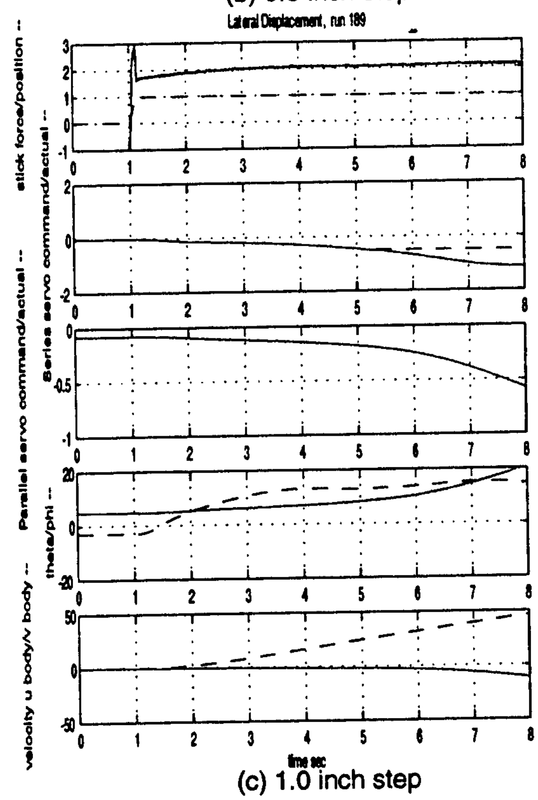
Figure 4: SP1A Pitch responses to force and displacement control inputs



(a) 1.75 lb force

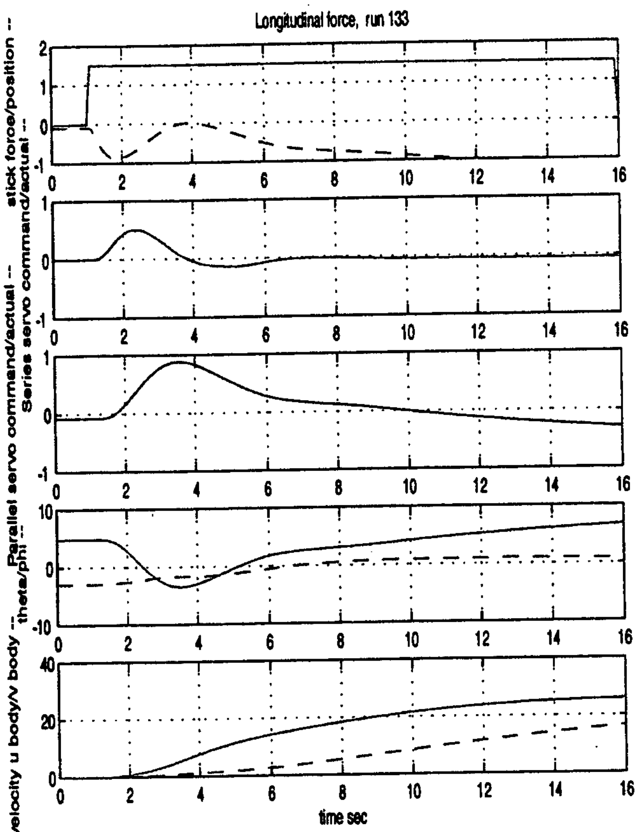


(b) 0.5 inch step

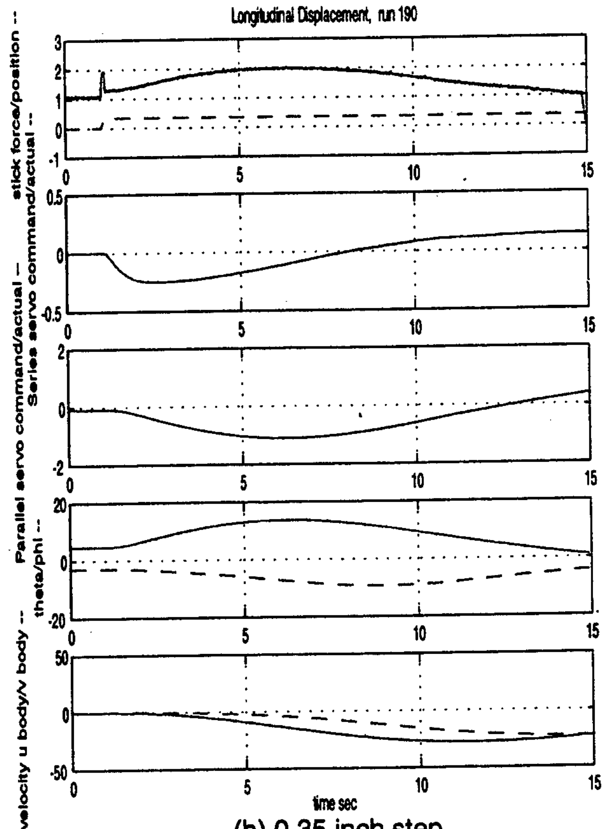


(c) 1.0 inch step

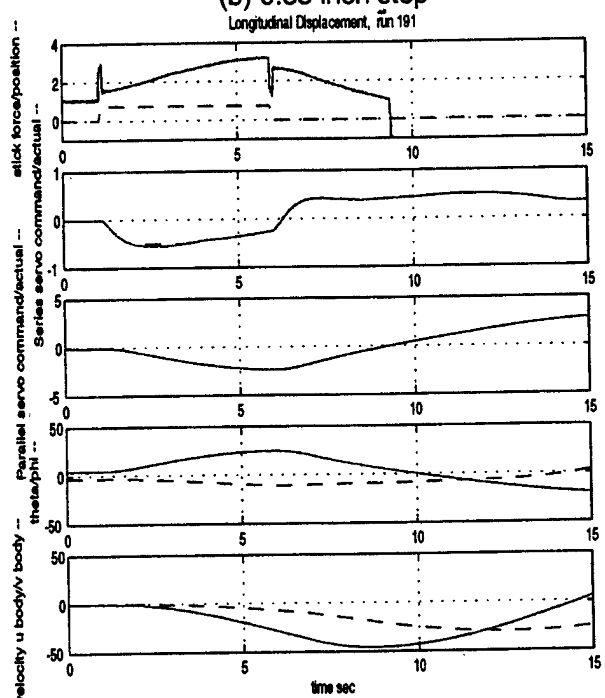
Figure 5: SP1A Roll responses to force and displacement control inputs



(a) 1.5 lb force

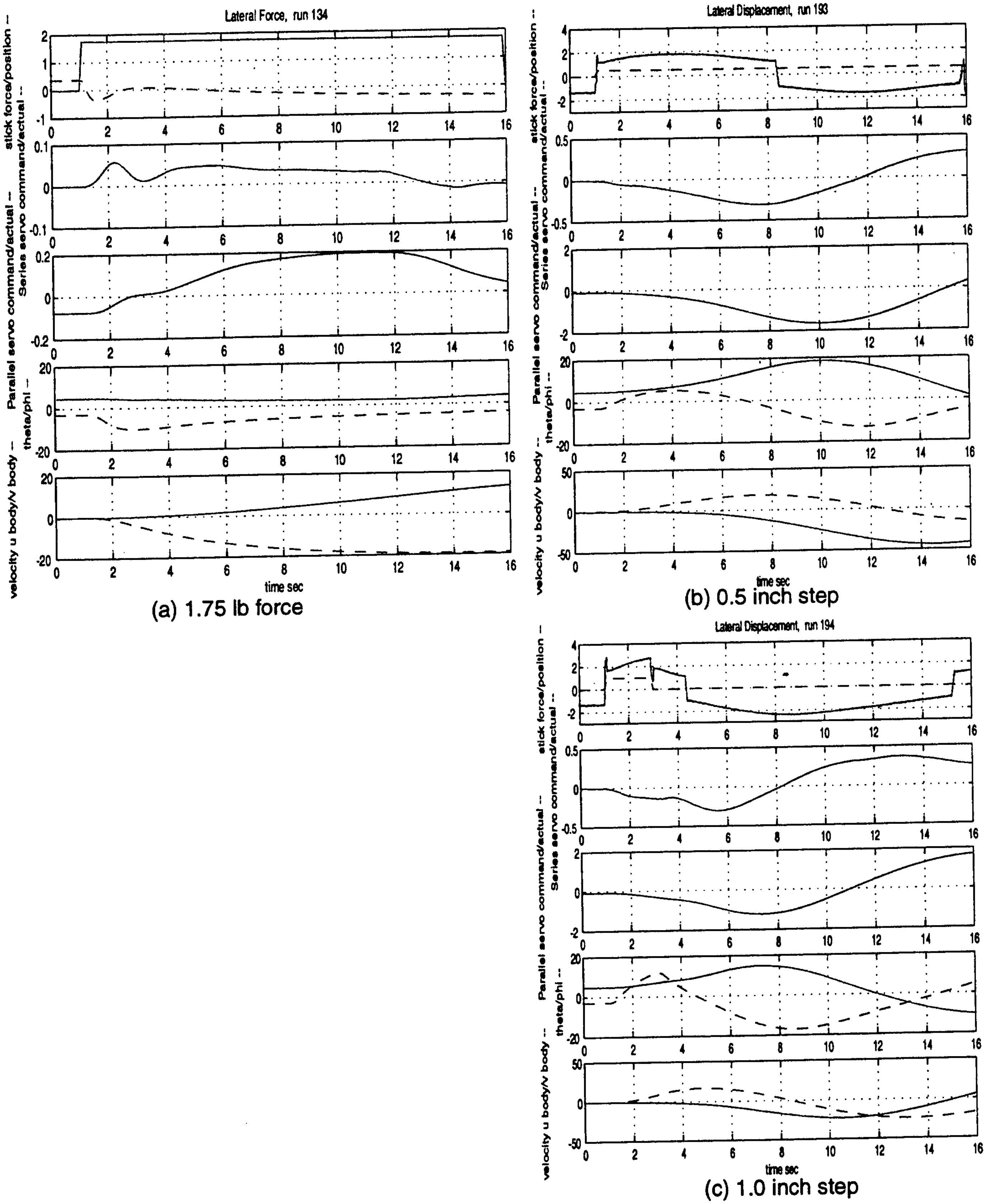


(b) 0.35 inch step



(c) 0.75 inch step

Figure 6: SP3A Pitch responses to force and displacement control inputs

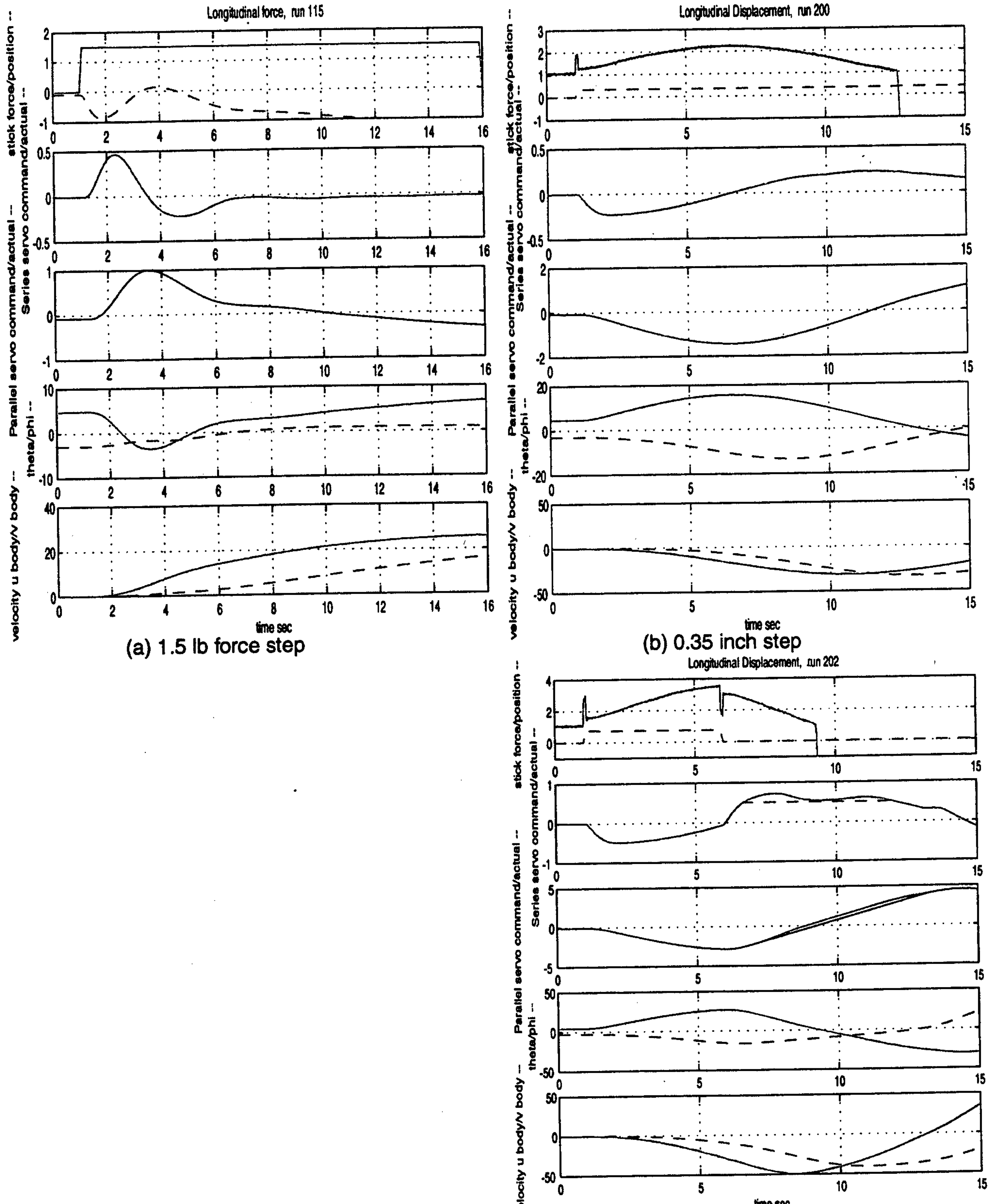


(a) 1.75 lb force

(b) 0.5 inch step

(c) 1.0 inch step

Figure 7: SP3A Roll responses to force and displacement control inputs

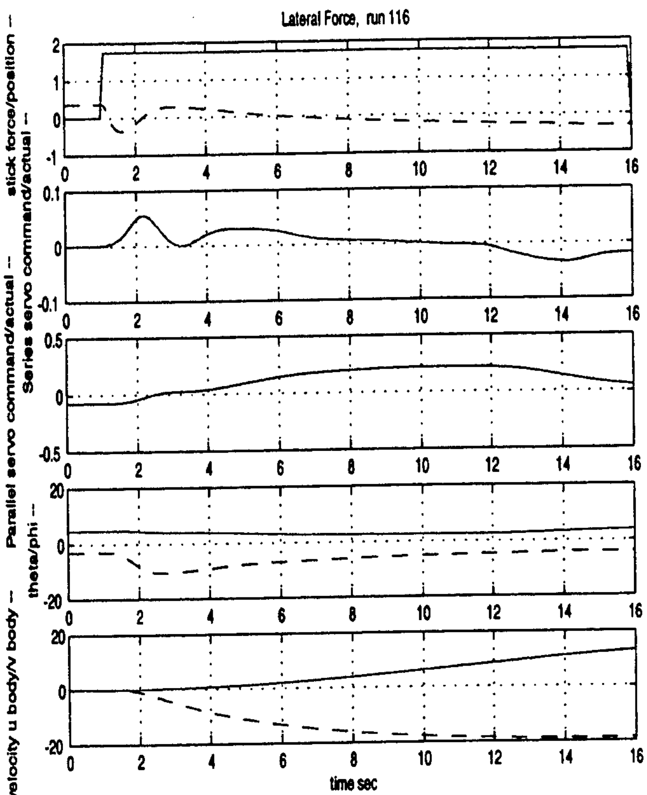


(a) 1.5 lb force step

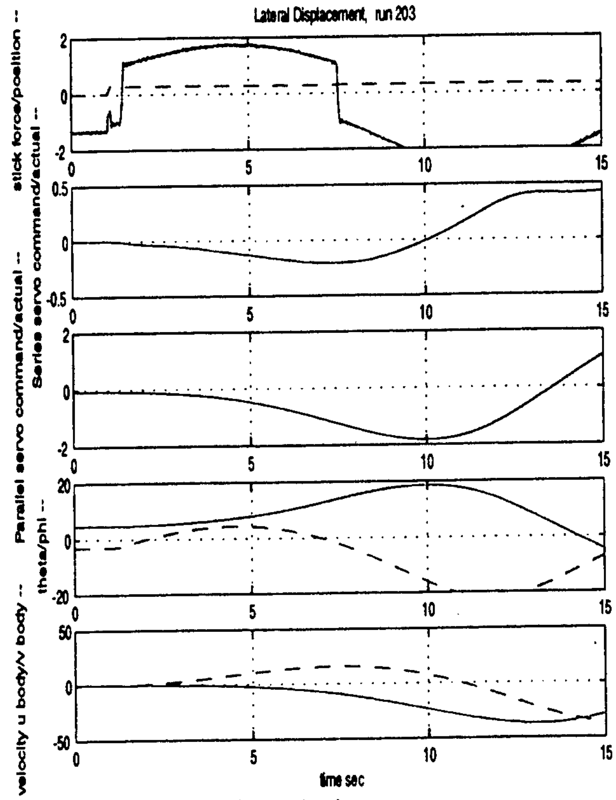
(b) 0.35 inch step

(c) 0.75 inch step

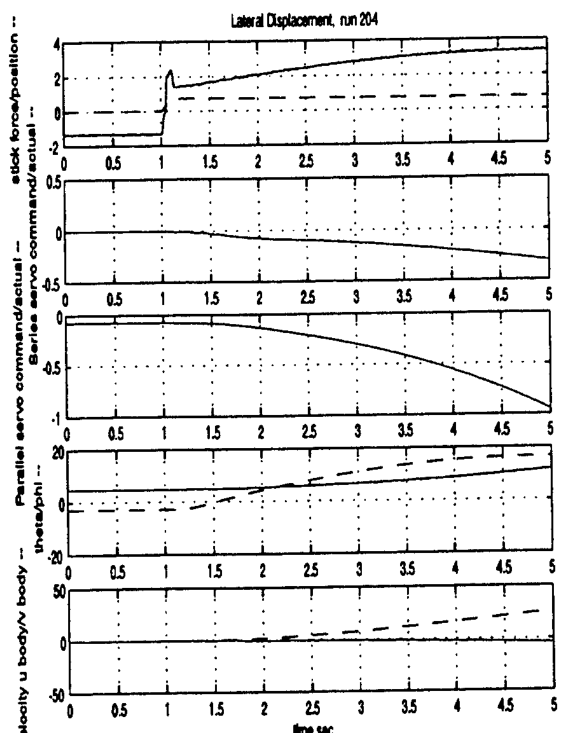
Figure 8: SP4B Pitch responses to force and displacement control inputs



(a) 1.75 lb force



(b) 0.3 inch step



(c) 0.75 inch step

Figure 9: SP4B Roll responses to force and displacement control inputs

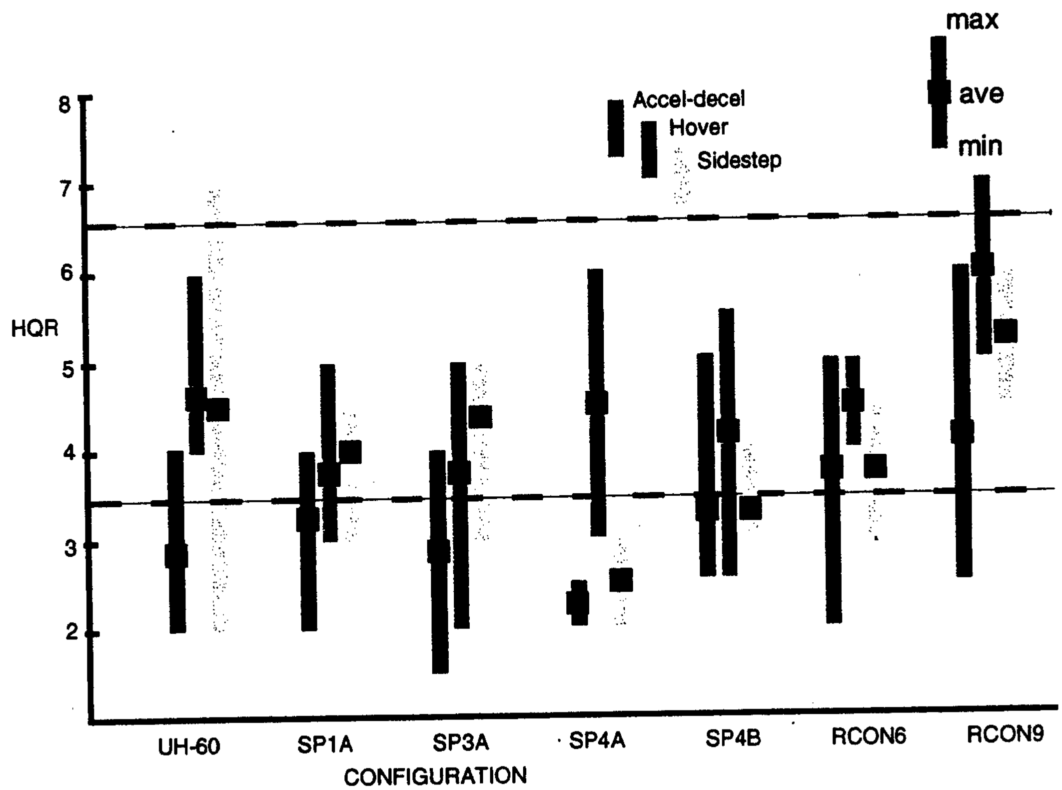


Figure 10: Composite plot of HQR, Height Hold on

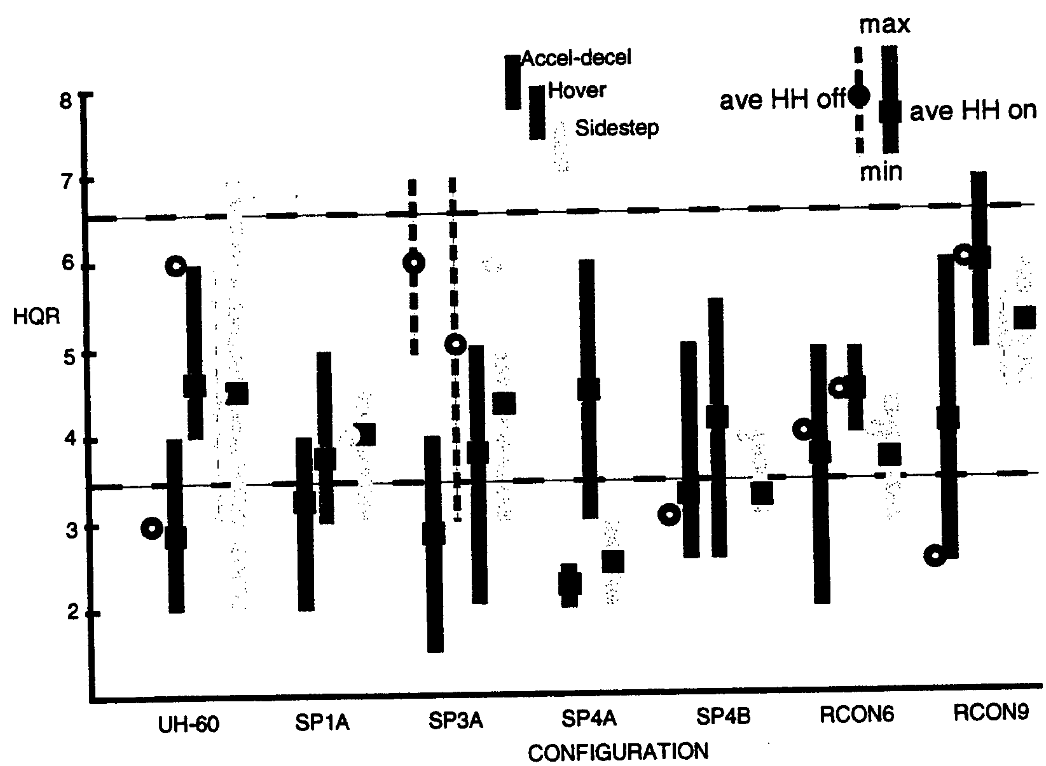


Figure 11: Effect of Height Hold

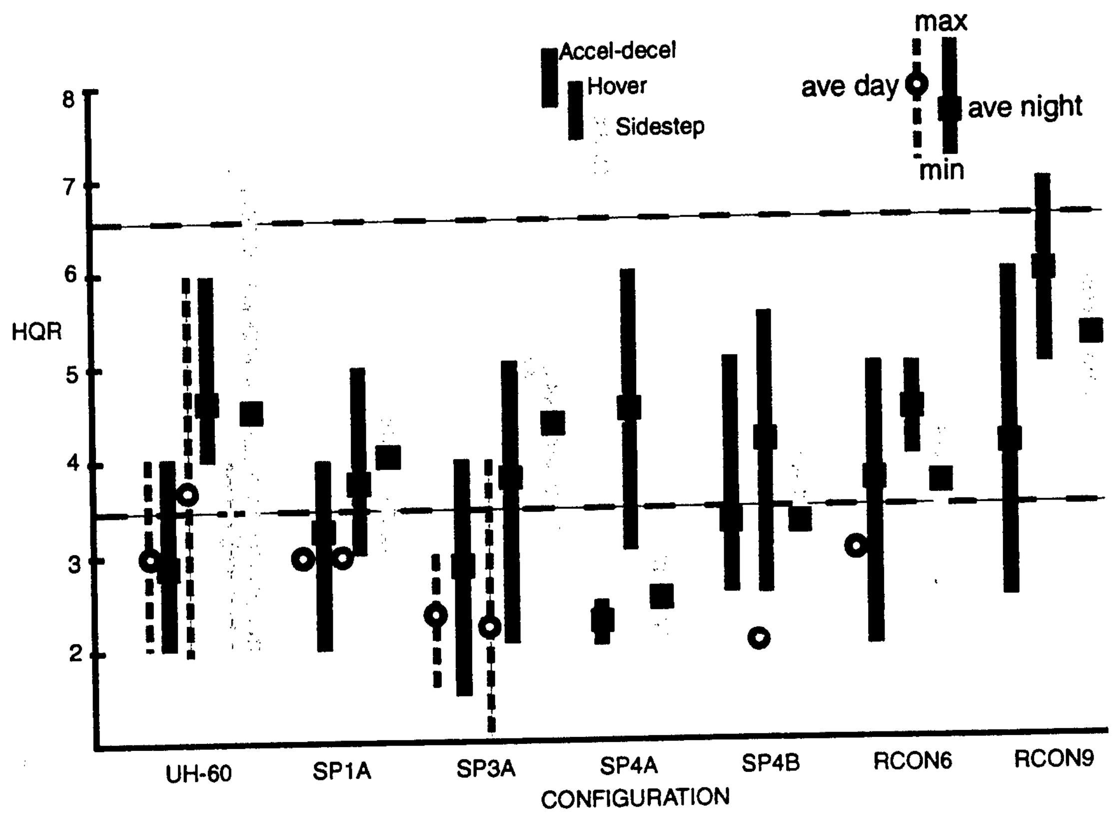


Figure 12: Effect of day visibility (UCE = 1)

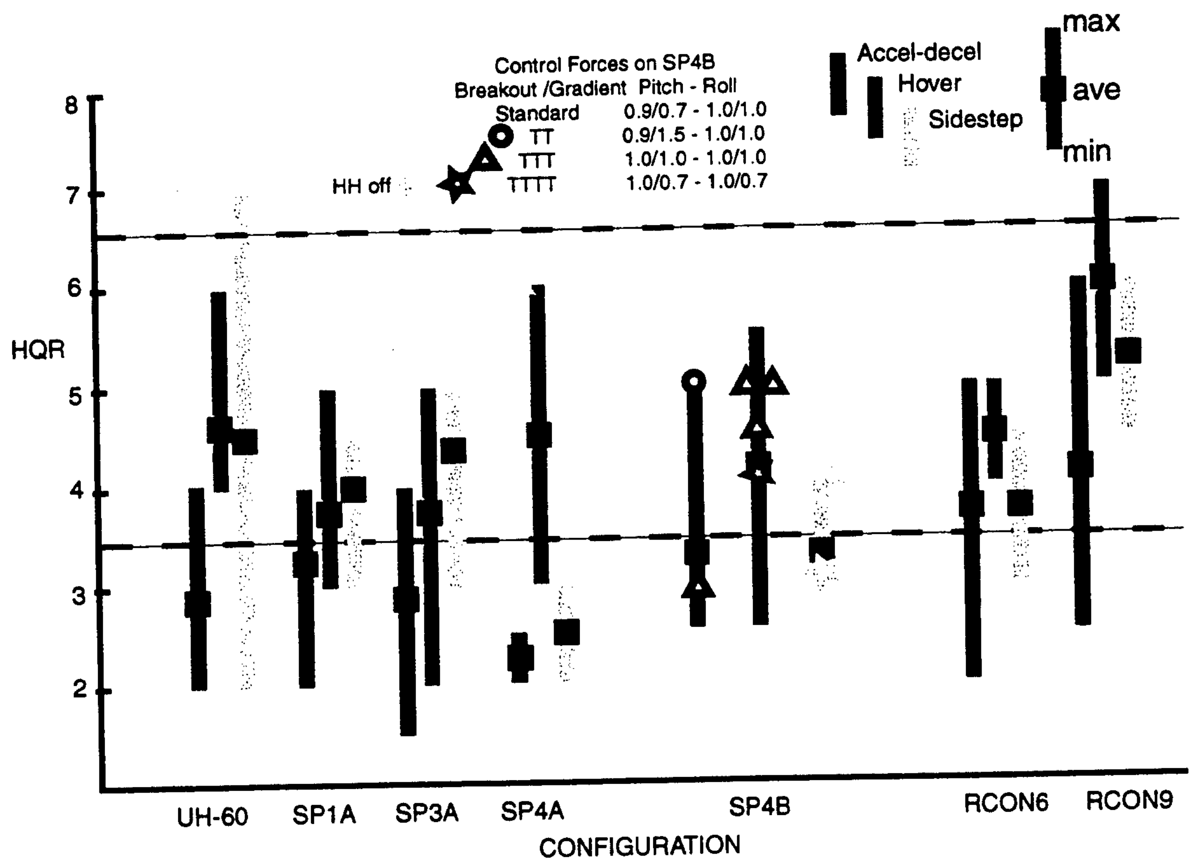


Figure 13: Effect of stick force gradient and breakout

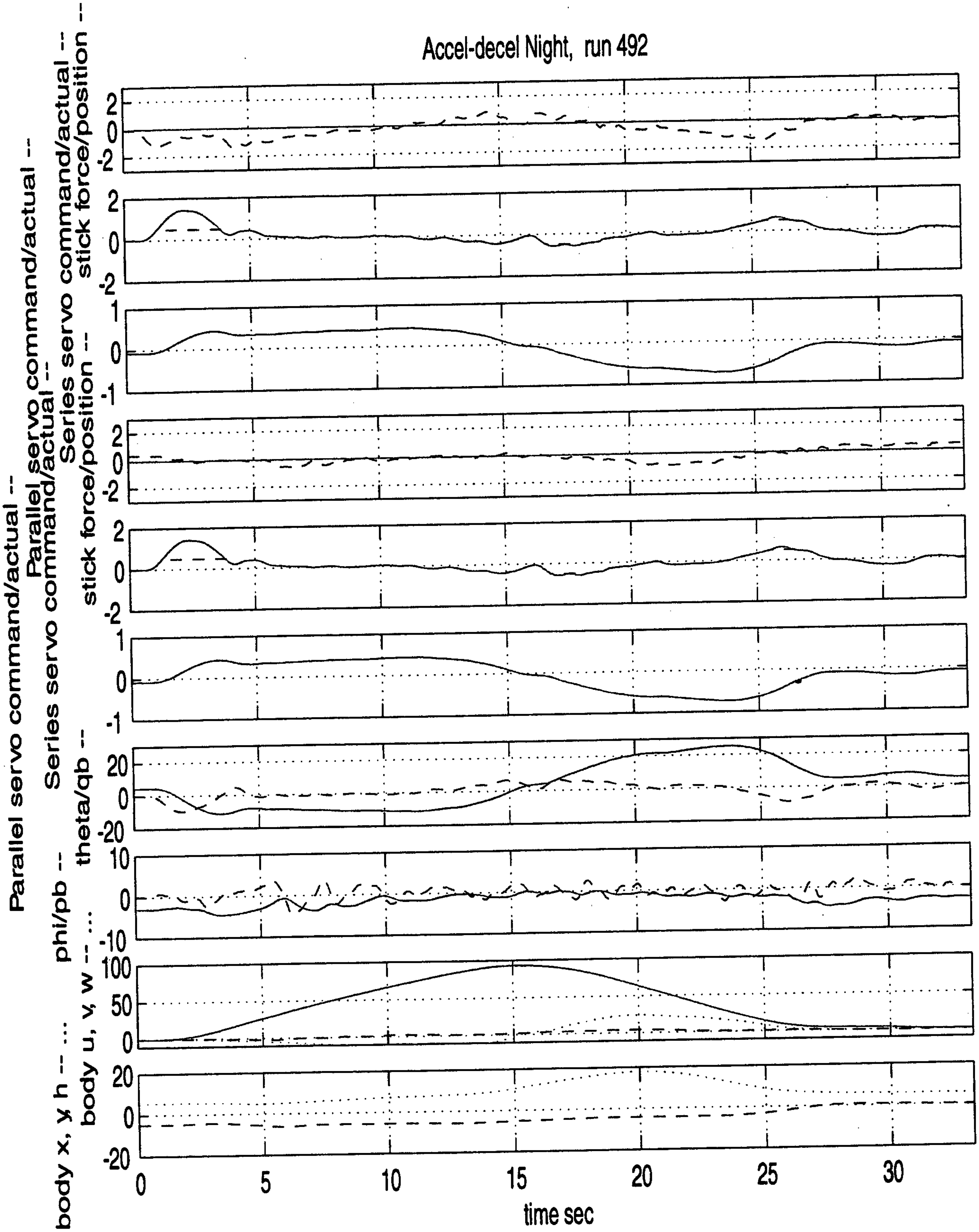


Figure 14: Acceleration deceleration time history for SP1A.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

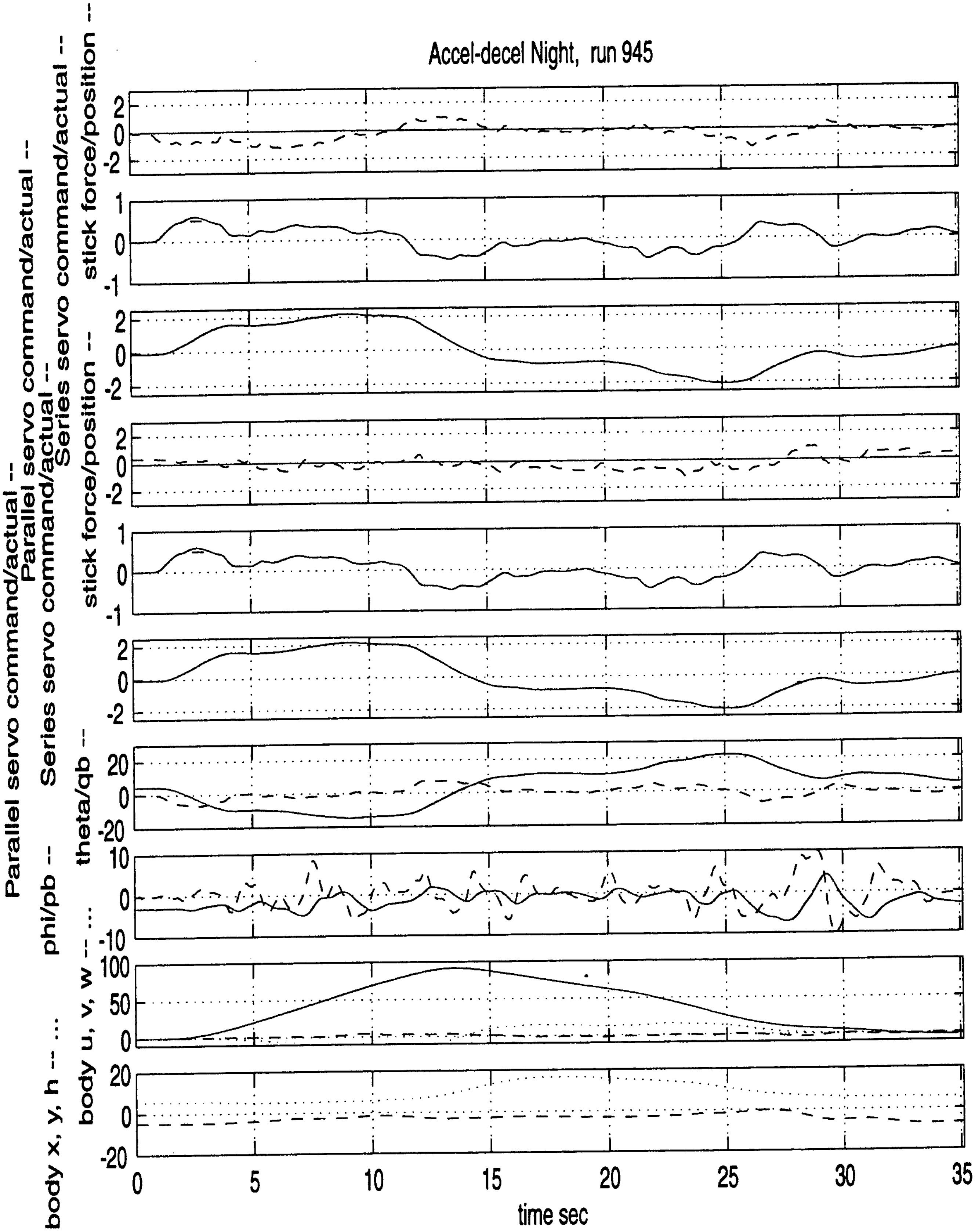


Figure 15: Acceleration deceleration time history for SP3A
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

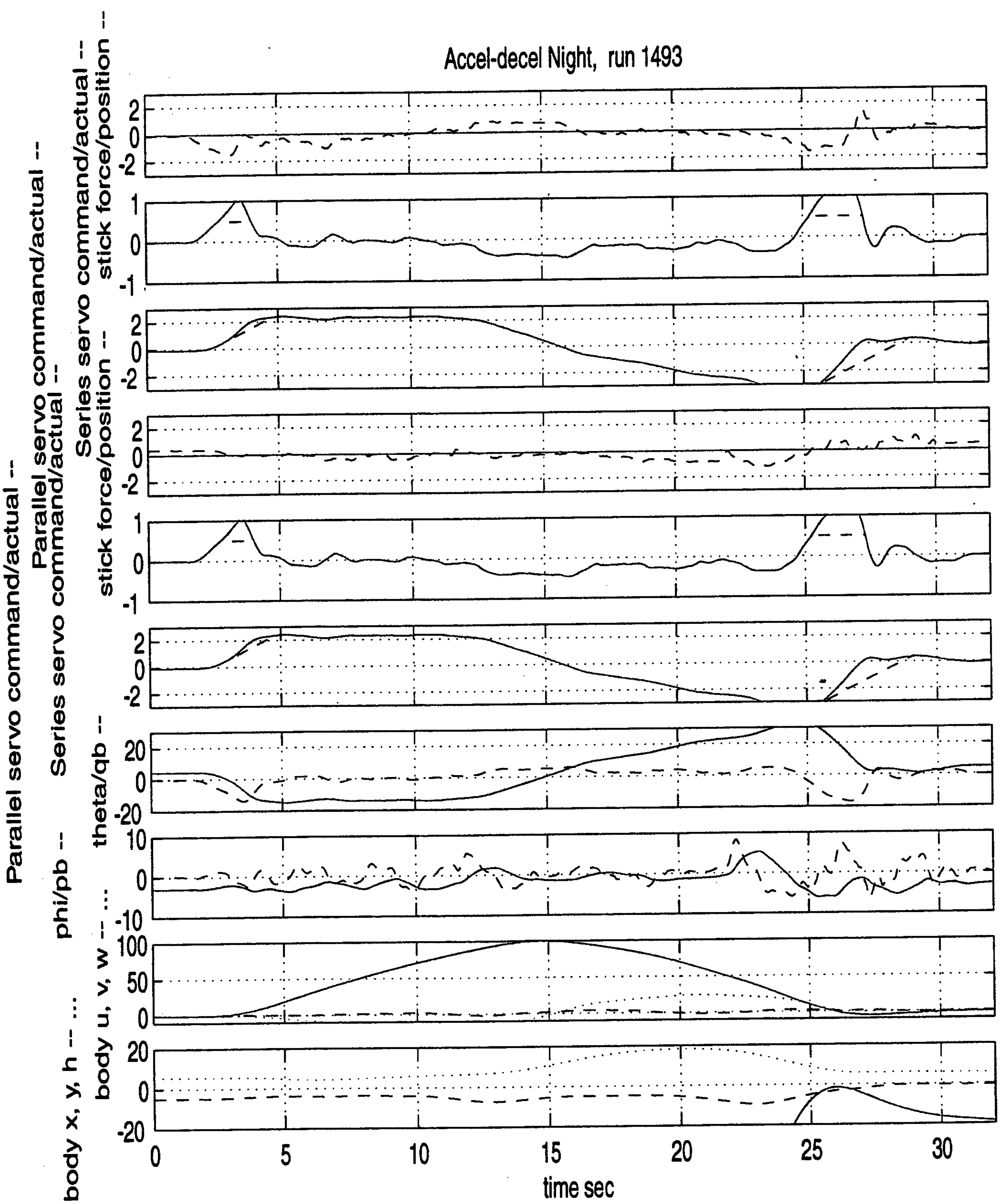


Figure 16: Acceleration deceleration time history for SP4B
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

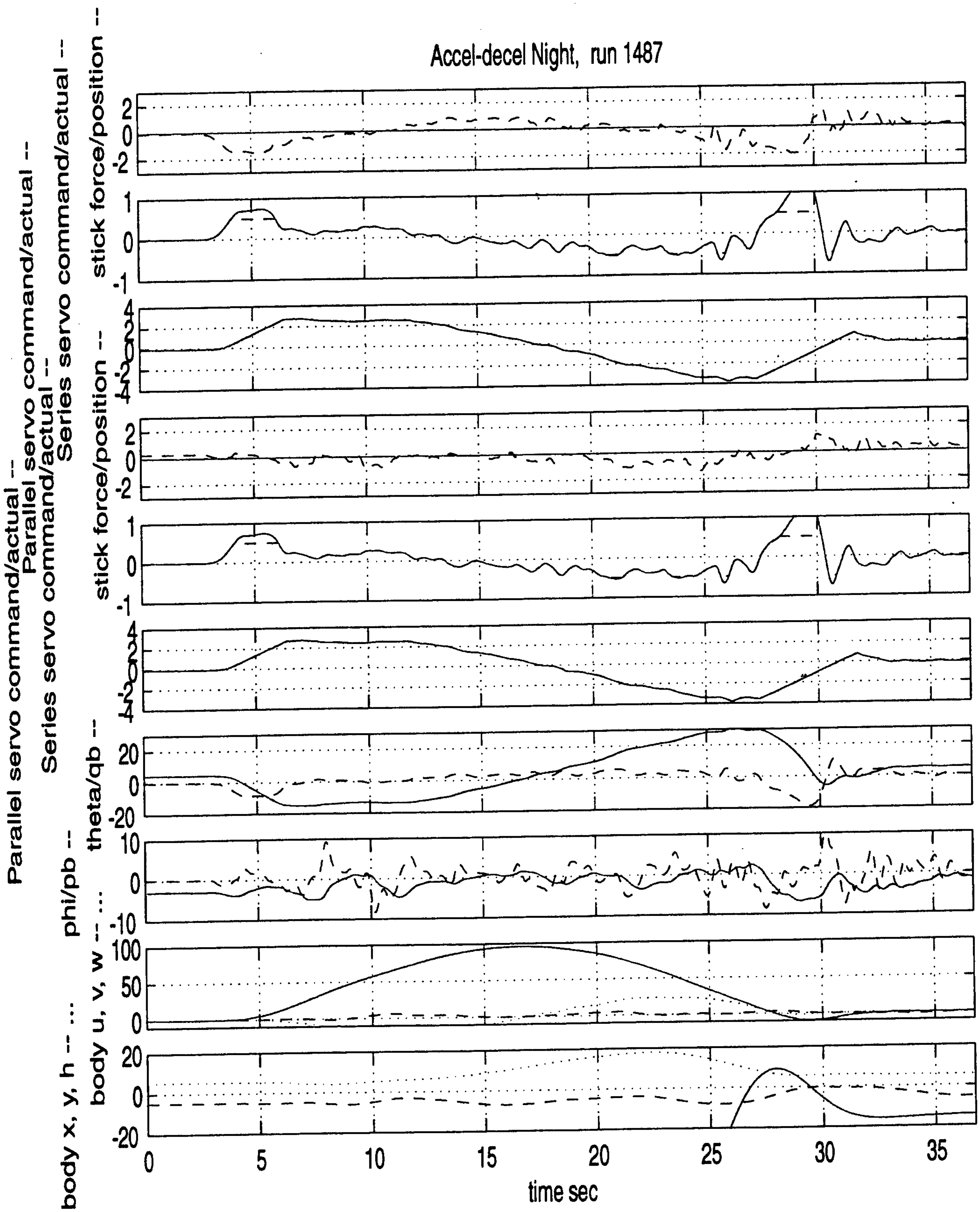


Figure 17: Acceleration deceleration time history for UH-60
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

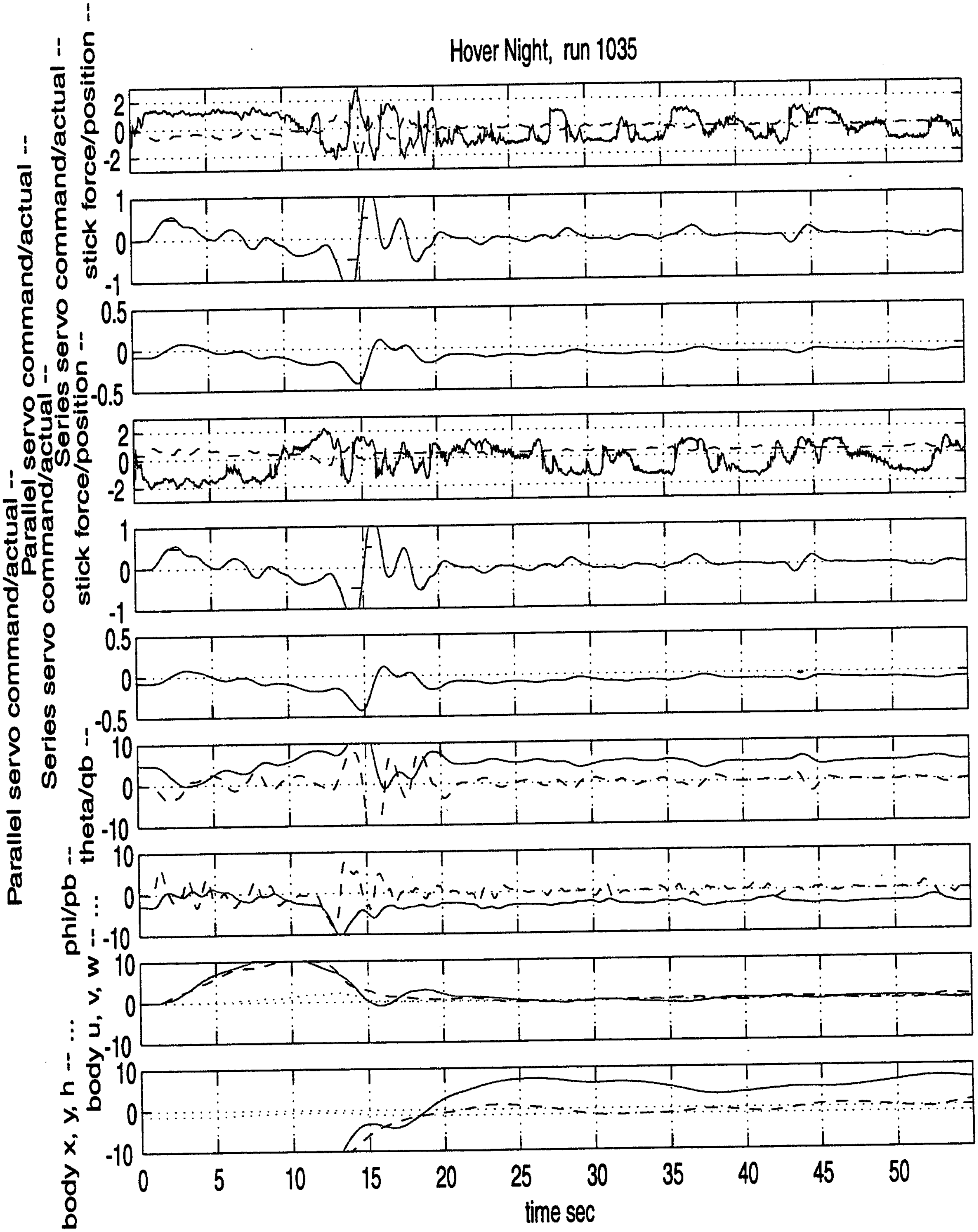


Figure 18: Hover time history for SP1A
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

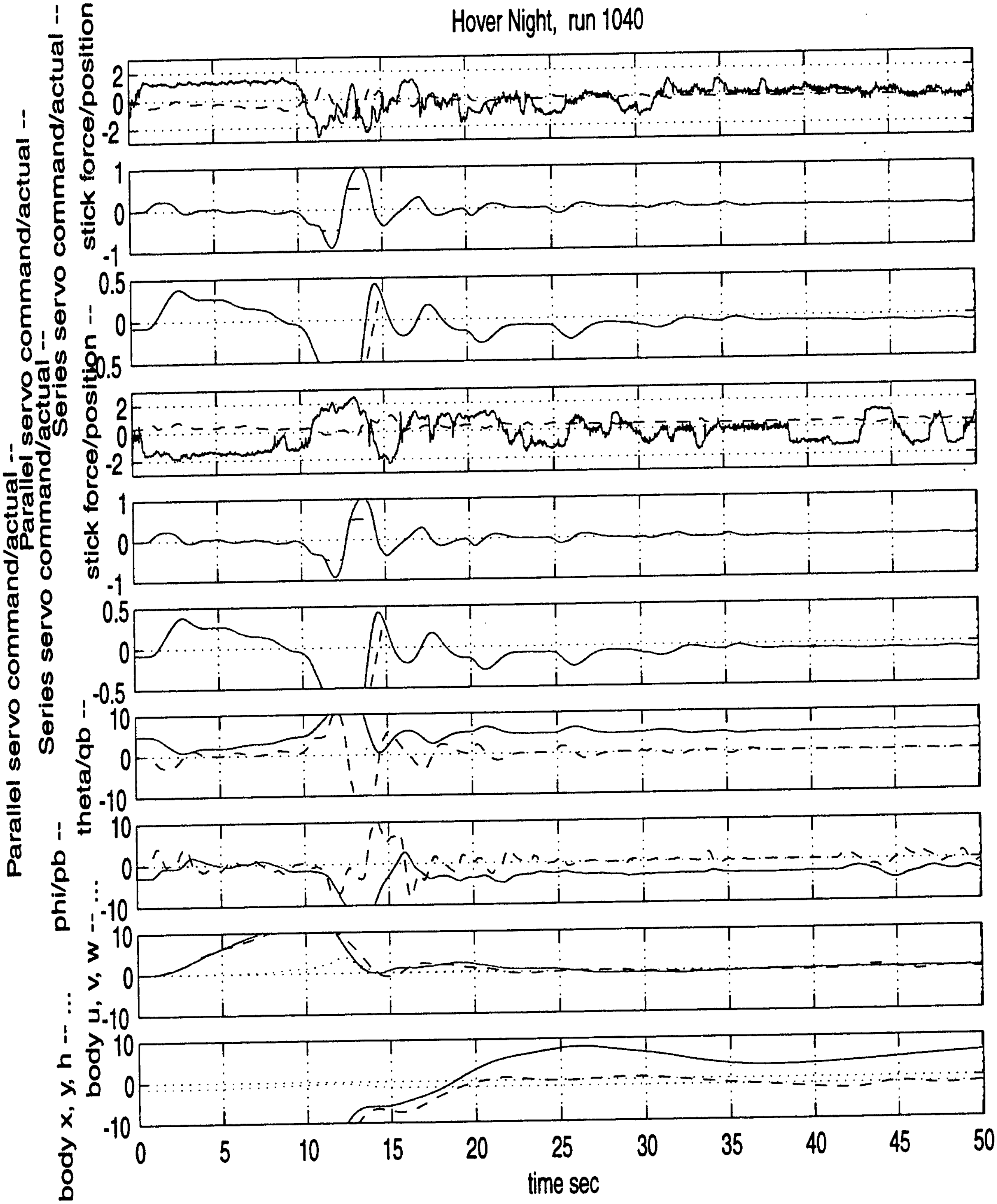


Figure 19: Hover time history for SP3A.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

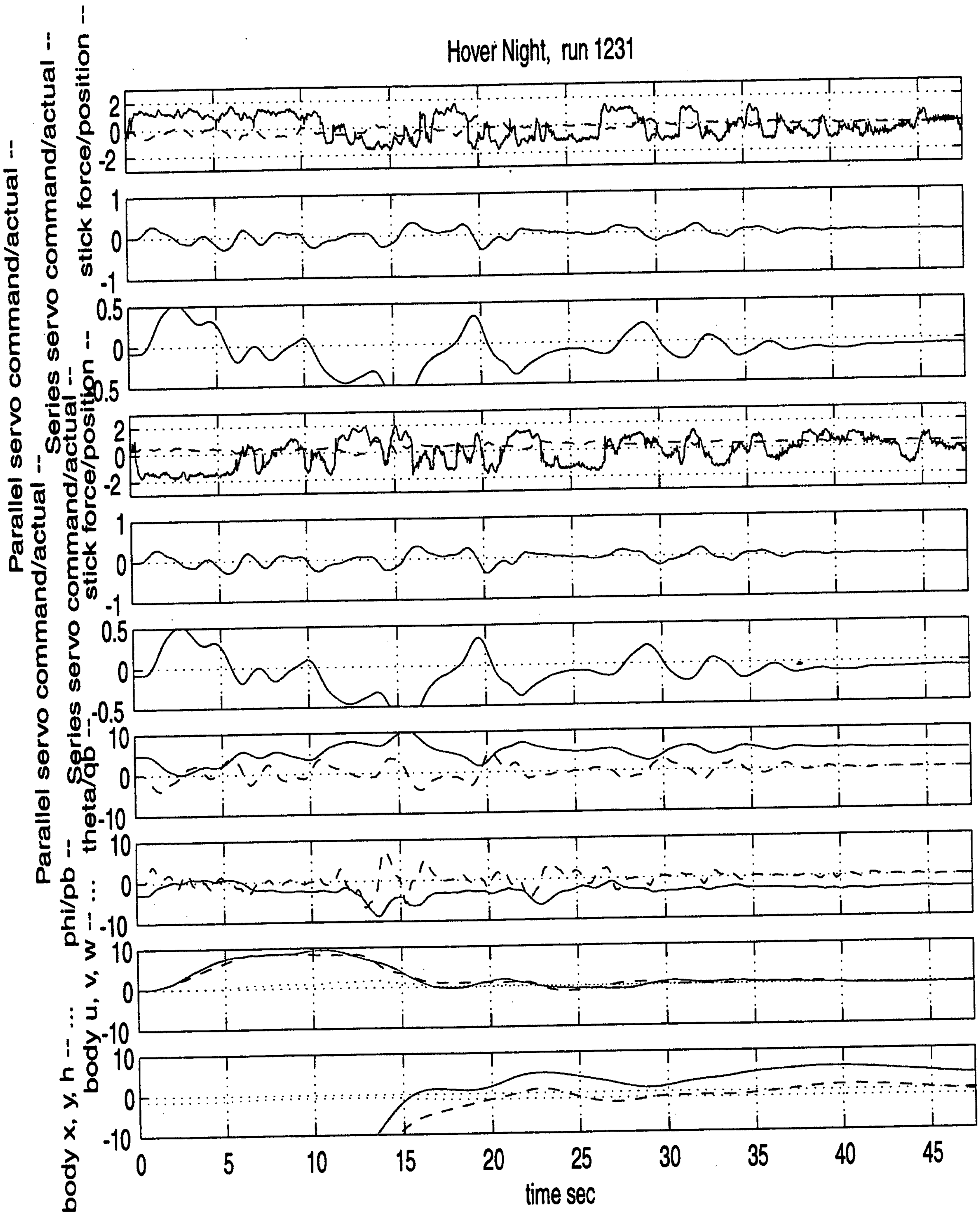


Figure 20: Hover time history for SP4B.
(Plots 1-3 longitudinal, 4-6 Lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

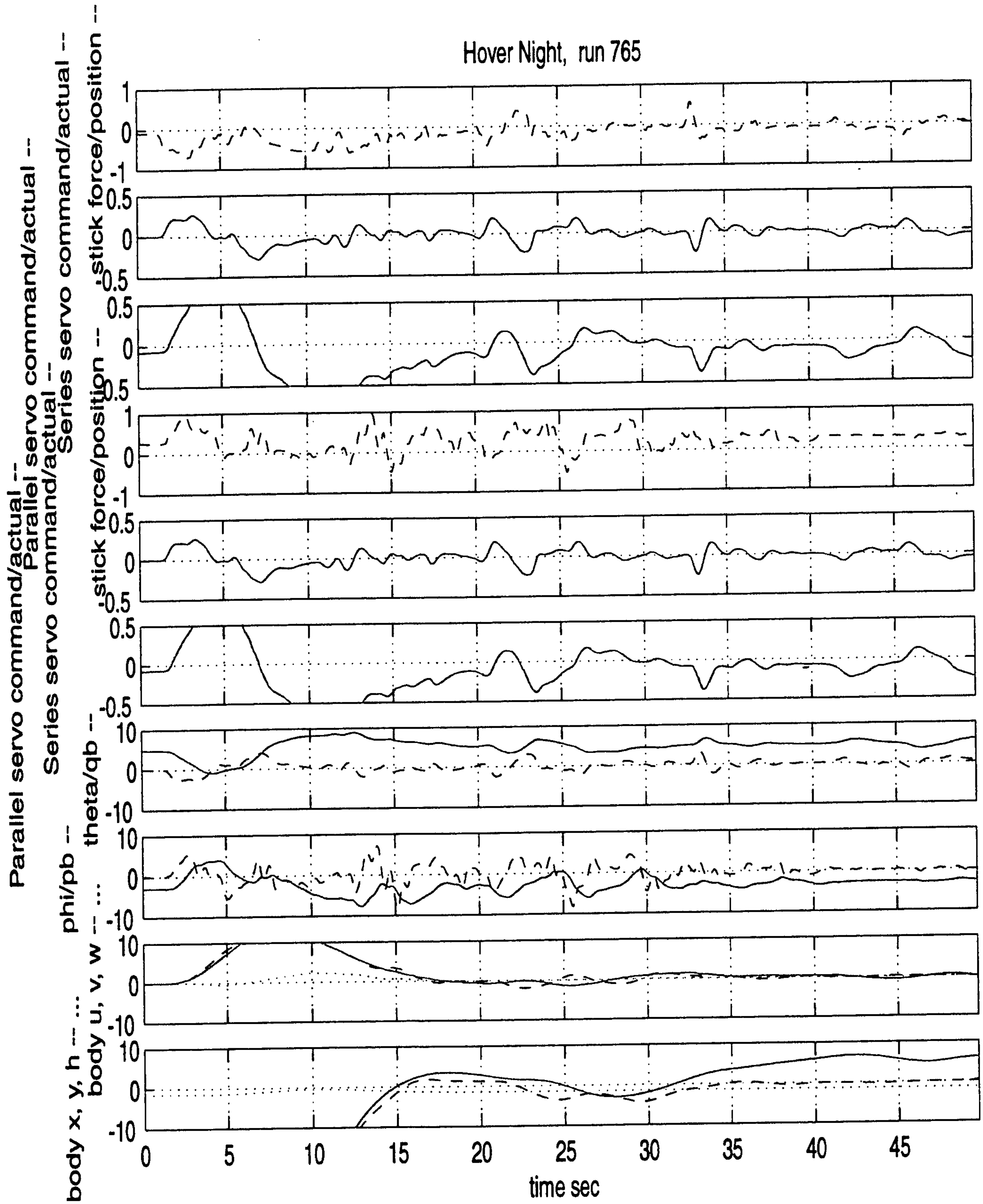


Figure 21: Hover time history for UH-60.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

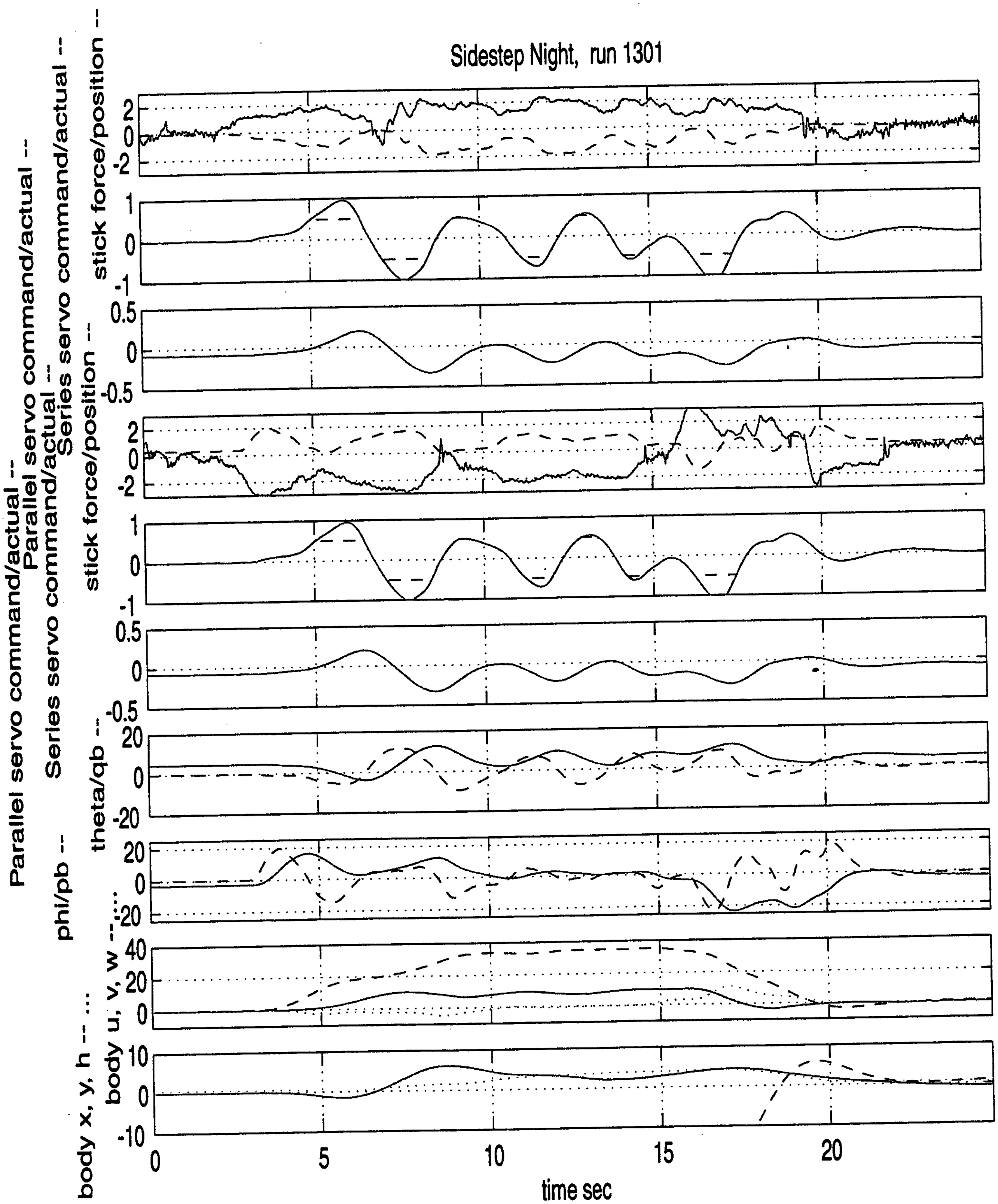


Figure 22: Sidestep time history for SP1A.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

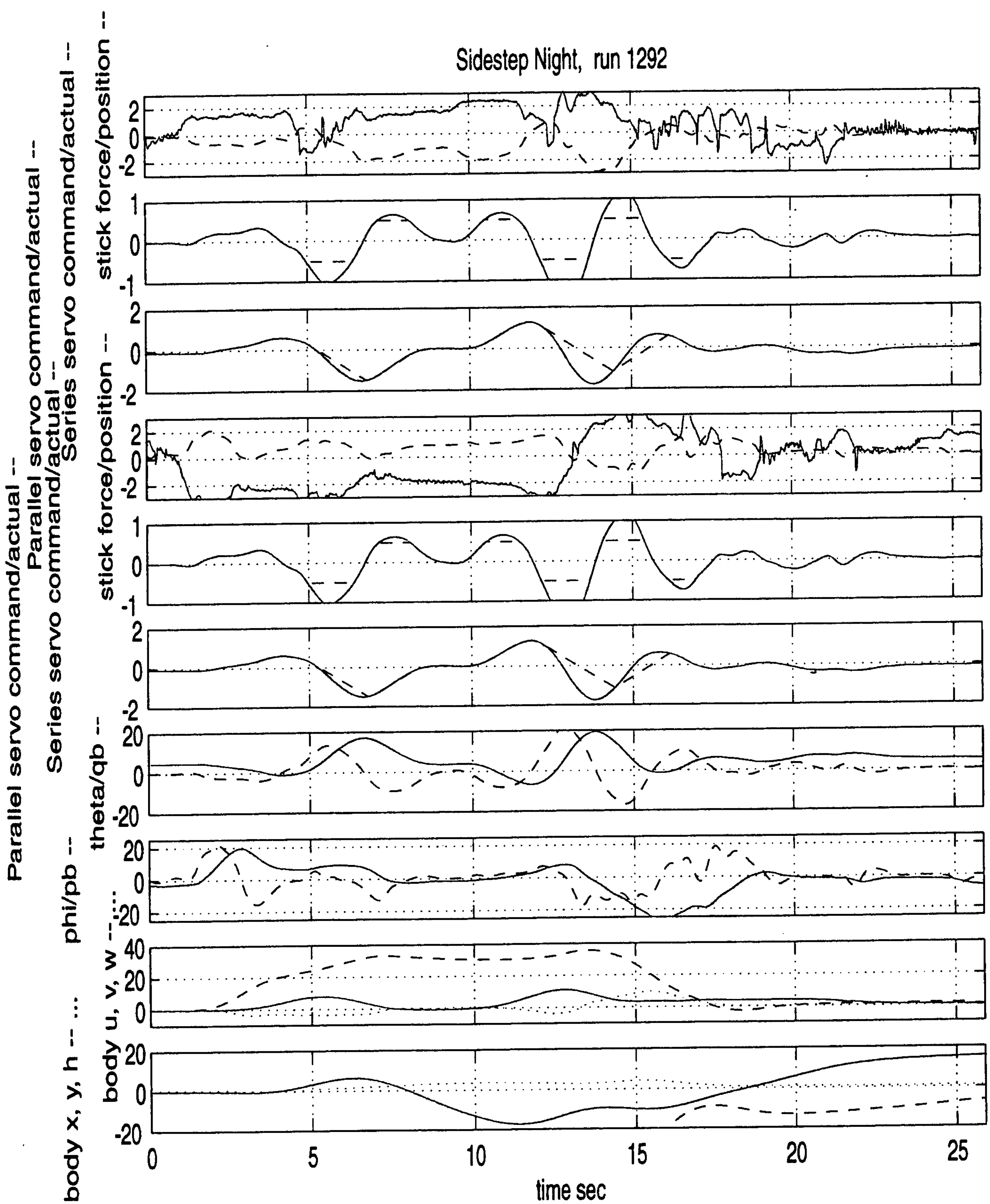


Figure 23: Sidestep time history for SP3A.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

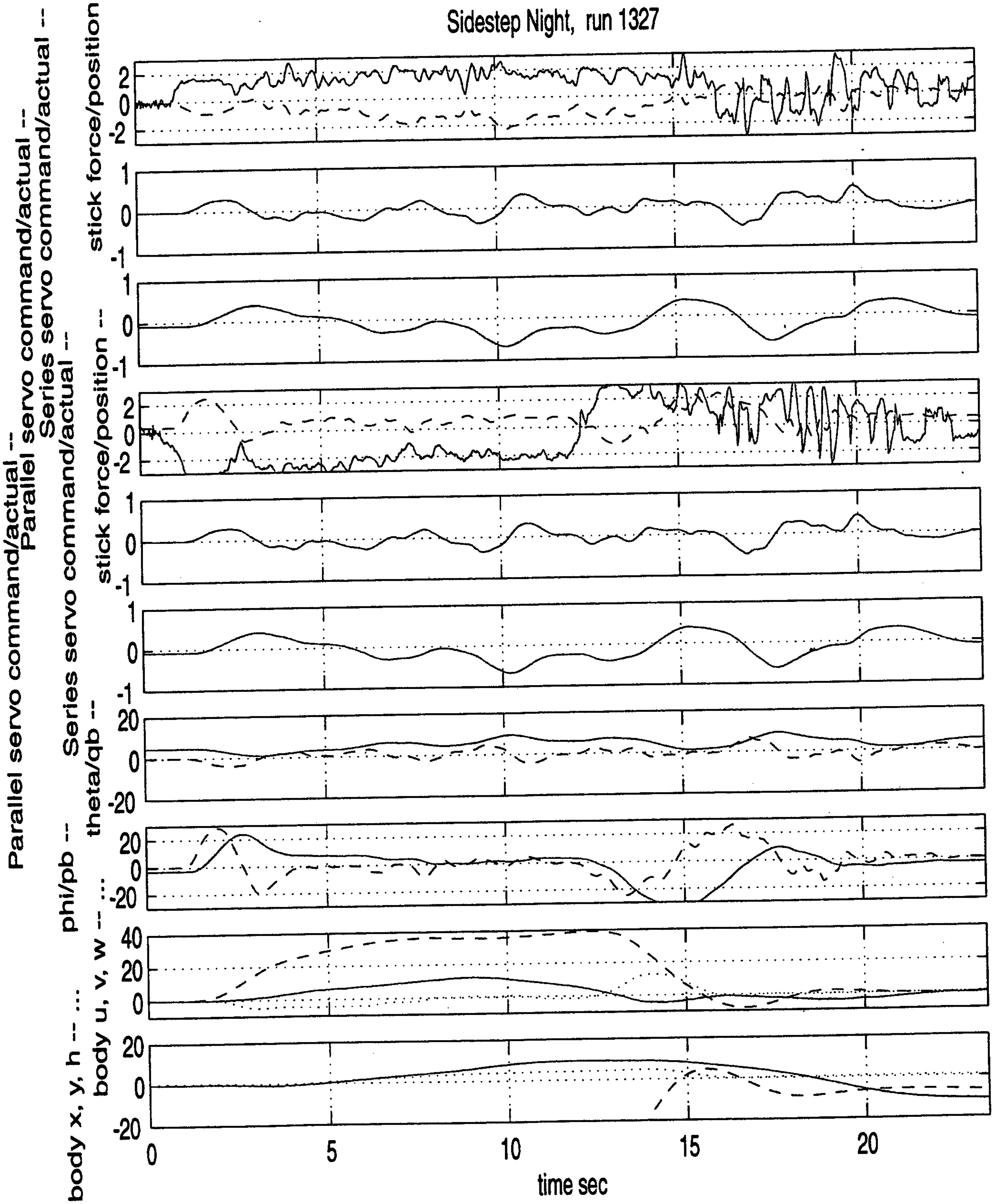


Figure 24: Sidestep time history for SP4B.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

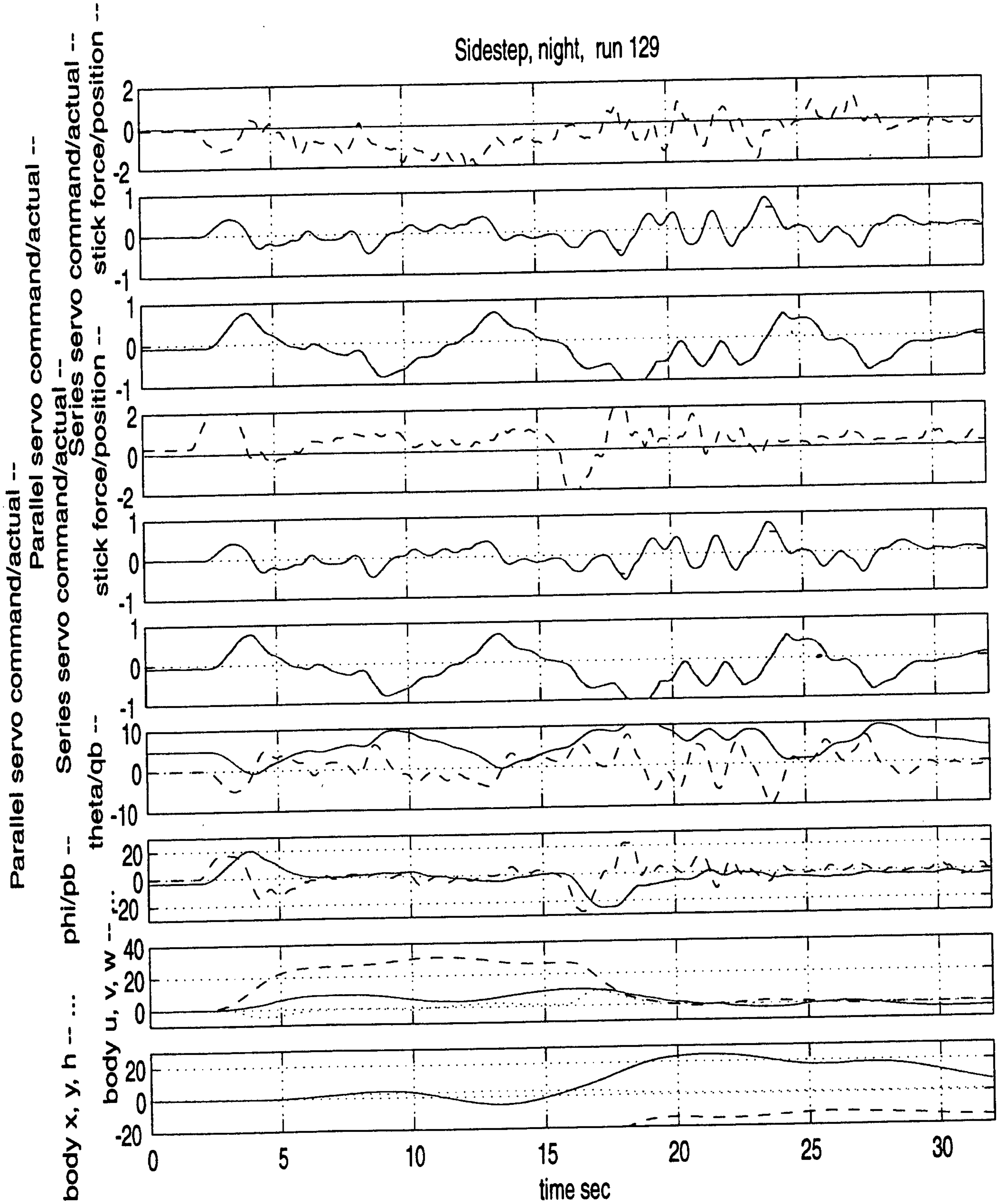
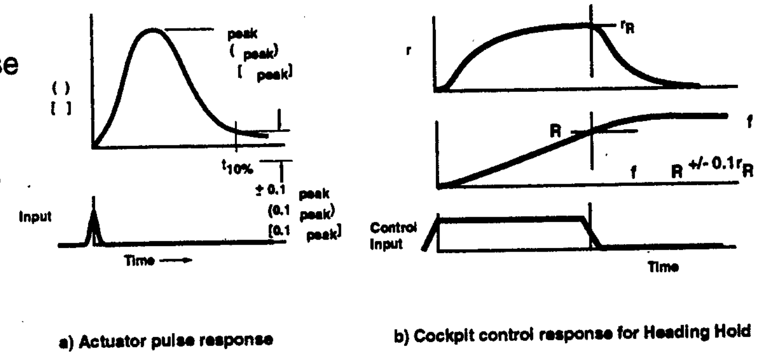


Figure 25: Sidestep time history for UH-60.
(Plots 1-3 longitudinal, 4-6 lateral. Units: pounds, inches, deg, deg/sec, ft/sec)

Figure A 1: Illustration of pulse response required for Attitude Hold and Direction Hold resonse types



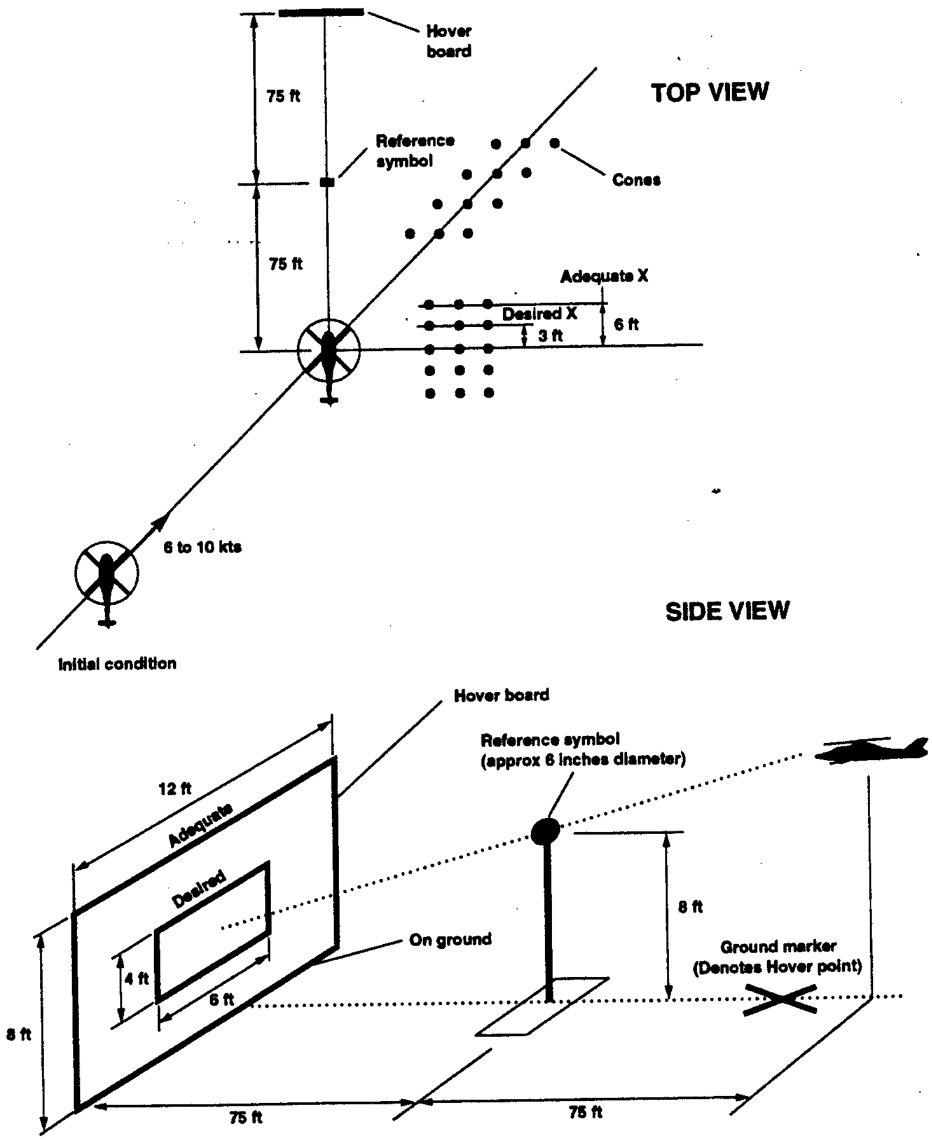


Figure B 1: Suggested course for Hover Maneuver

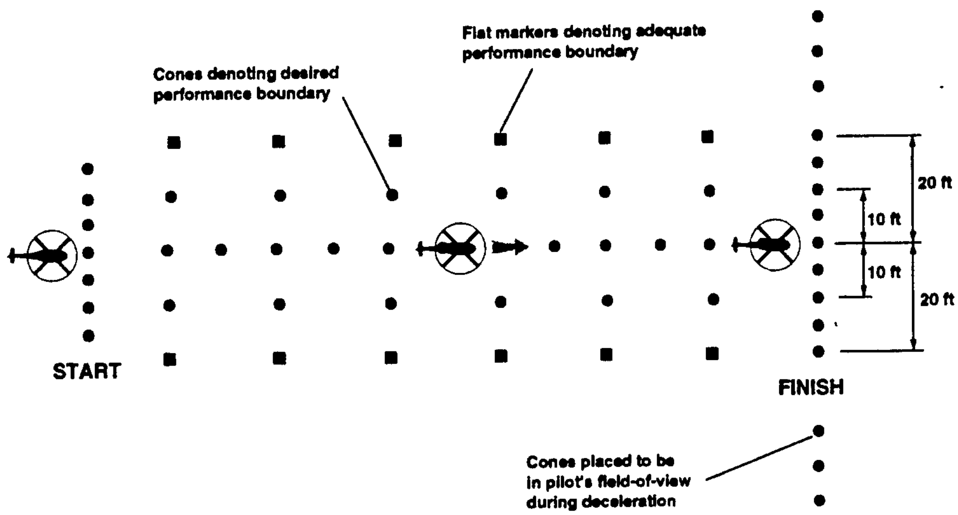


Figure B 2: Suggested course for acceleration deceleration maneuver

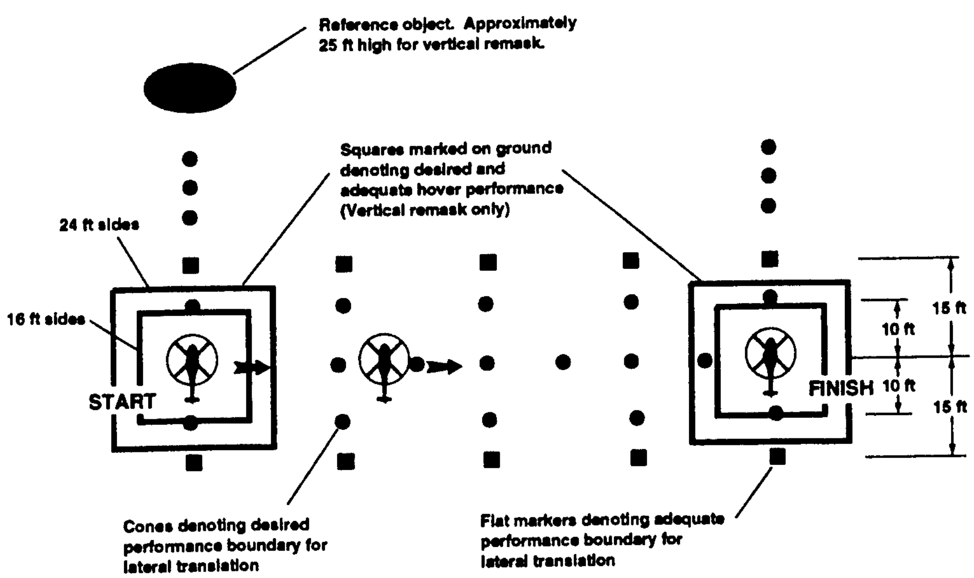


Figure B 3: Suggested course for sidestep maneuver

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
January 2002

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
Piloted Simulation Investigation of Techniques to Achieve Attitude Command Response with Limited Authority Servos — Final Report Mar 1996—Nov 2001

5. FUNDING NUMBERS
NAS2-14360

6. AUTHOR(S)
David L. Key and Robert K. Heffley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Hoh Aeronautics, Vista Verde Center #217, 2075 Palos Verdes Drive N, Lomita, CA 90717, and Aeroflightdynamics Directorate, U.S. Army Aviation and Missile Command (AMRDEC), Ames Research Center, Moffett Field, CA 94035

8. PERFORMING ORGANIZATION REPORT NUMBER
A-0207144

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration, Washington, DC 20546-1000 and U.S. Army Aviation and Missile Command, Redstone Arsenal, AL 35898-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM—2002-211391
AFDD/TR-02-A-003

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited
Subject Category 08 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
The purpose of the study was to develop generic design principles for obtaining attitude command response in moderate to aggressive maneuvers without increasing SCAS series servo authority from the existing ±10%. In particular, to develop a scheme that would work on the UH-60 helicopter so that it can be considered for incorporation in future upgrades. The basic math model was a UH-60A version of GENHEL. The simulation facility was the NASA-Ames Vertical Motion Simulator (VMS). Evaluation tasks were Hover, Acceleration-Deceleration, and Sidestep, as defined in ADS-33D-PRF for Degraded Visual Environment (DVE). The DVE was adjusted to provide a Usable Cue Environment (UCE) equal to two. The basic concept investigated was the extent to which the limited attitude command authority achievable by the series servo could be supplemented by a 10%/sec trim servo. The architecture used provided angular rate feedback to only the series servo, shared the attitude feedback between the series and trim servos, and when the series servo approached saturation the attitude feedback was slowly phased out. Results show that modest use of the trim servo does improve pilot ratings, especially in and around hover. This improvement can be achieved with little degradation in response predictability during moderately aggressive maneuvers.

14. SUBJECT TERMS
Rotorcraft, Stability and control, Handling qualities, Attitude command

15. NUMBER OF PAGES
67

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL